第二届宝钢学术年会

The Second Baosteel Biennial Academic Conference

Proceedings

of the Second Baosteel Biennial Academic Conference

谢企华　徐乐江　主编

Edited by

XIE Qihua & XU Lejiang

Volume 1

会议主题：技术创新与循环经济

Theme: Technology Innovation and Circular Economy

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编 委 会

Editorial Committee

前　言

两年前的五月，这里曾经举办了首届宝钢学术年会，就“可持续的钢铁，可持续的未来”这一主题，开展了广泛的交流，得到了各界朋友们的大力支持和热情参与，收到了很好的效果，至今我们还记忆犹新。

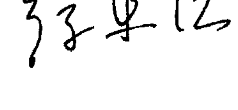
今天，我们再次相聚在黄浦江畔，倍感愉快。本届年会的主题是“技术创新与循环经济”。这是上届年会主题的延伸和深化。在我们国家，正在执行着以人为本，全面、协调、可持续的科学发展观。国民经济新一轮的发展规划，对冶金界的节能降耗和环境保护，提出了更加严格的要求。

两年来，世界粗钢产量连续突破10亿和11亿吨，2005年比2004年又增长5.9%，其中有一半以上出产在亚洲地区；增长的部分几乎全部来自发展中国家。钢铁产品仍然具有十分广阔的市场空间；钢铁仍然是不可替代的工程材料；钢铁仍然对世界经济发展起着举足轻重的作用。

但是，人们也充分意识到，过大的资源消耗与过重的环境负担，已构成钢铁工业可持续发展的制约因素。要缓解这种制约、越过这一瓶颈，就要走节能降耗之路，就要走循环经济之路。要开辟这样的路，就只能靠技术进步与创新，靠技术创新来推动可持续发展。

本届年会共收到国内外作者的技术论文400余篇。经专家认真筛选，将其中的240篇收入本论文集中。论文集共分为3册。

在此，我们衷心感谢论文的作者、年会学术委员会成员、顾问、专家、筹备人员和论文集编辑人员为年会成功召开与论文集出版所做的贡献，因时间仓促，文集中缺点和错误在所难免，期盼大家提出宝贵的意见。



宝钢集团有限公司总经理

PREFACE

Two years ago in May, the first Baosteel Biennial Academic Conference (BAC) was held here, during which extensive exchanges were conducted on the theme of "the sustainable steel the sustainable future". The conference has achieved fruitful results thanks to the energetic support and active participation of friends from all walks of life, which still remains fresh in our memory.

Today, we are delighted to gather again on the riverside of Huangpu River. The theme of this conference is "technology innovation and circular economy", an extension and deepening of the theme of the previous BAC. A comprehensive, harmonious and sustainable scientific outlook on development featuring people first is being implemented in the country. The new round of development planning of national economy puts forward more stringent requirements on metallurgical industry for energy saving, consumption reduction and environmental protection.

The world crude steel output exceeded 1 and 1.1 billion tons respectively in the past two years. The year 2005 witnessed a global output increase by 5.9% over the previous year, almost all coming from developing countries and over half of which was contributed by Asia. There is still a big potential market for steel products; steel remains an irreplaceable engineering material; it still plays a vital role in the economic development of the world.

However, we fully recognize the fact that excessive energy consumption and overburden to the environment have constrained the sustainable development of steel industry. To relax the constraint and overcome the bottlenecks, we need to embark on a road of circular economy featuring energy saving and consumption reduction through technological progress and innovation which propel the sustainable development.

Among the over 400 technical papers contributed by both domestic and overseas authors, 240 of them have been chosen and placed in the proceedings (in three volumes) after a professional and careful selection.

Hereby, heartfelt gratitude is extended to authors, members of the academic committee of the conference, advisors, experts, staff of the preparatory committee and editing team of the proceedings, for their great devotion and contribution to the successful convening of the conference as well as the publication of the proceedings. Due to limitation of the time, the proceedings still have a great potential for further improvement. We are sincerely looking forward to your precious advices.

XU Lejiang

President of Baosteel Group Corporation

CONTENTS

Carbon Steel and Its Process

Discrete Particle Simulation Applied to Blast Furnace Modelling

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(1. Center for Simulation and Modelling of Particulate Systems and School of Materials Science and Engineering, University of New South Wales, Sydney, NSW 2052, Australia; 2. Bluescope Steel Research, P. O. Box 202, Port Kembla, NSW 2505, Australia)

Abstract: The paper presents a brief review of the recent studies of particle and particle – fluid flow in an ironmaking blast furnace (BF) by means of discrete particle simulation coupled with the conventional computational fluid dynamics. The key features of this method are described first. Then the results are discussed with reference to four research areas in BF modelling: burden distribution at the top, gas – solid flow in the shaft, gas – solid flow in the raceway, and solid flow in the hearth. It is shown that this approach does capture the main features of the complex BF flow and is an effective way to generate particle scale information for better fundamental understanding.

Keywords: discrete particle simulation; blast furnace; solid flow; particle – fluid flow

0 Introduction

Blast furnace (BF) ironmaking is an important technology by which iron is efficiently reduced from iron – bearing particles. This is a very complicated chemical process in which the layered coke and ore particles are charged from bell or bell – less top, then descend along the BF shaft due to gravity. During the descent, ore is reduced, becomes liquid (slag and iron) in the cohesive zone and then flows into the hearth. The coke is partially gasified before flowing into the raceway, where it combusts with hot blast (naturally – humidified, oxygen – enriched air) to form reducing gas and heat. These reducing gases rise through the particle bed and escape from the top. Therefore, a modern BF is a high temperature reactor involving complex gas – liquid – powder – solid four – fluid flow. Understanding and modelling this complex multi – phase flow system has been a focus of research in the past decades (see[1, 2] for example).

Of particular interest here is the flow of solids, which is closely related to the permeability control and, to a large degree, governs the flow of other phases. Physical modelling has been used for years (see[3 ~ 5] for example). Recent research efforts are mainly made on mathematical modelling which can be generally classified into two categories: the continuum approach at a macroscopic level and the discrete approach at a microscopic level[6]. The continuum approach, based on local average principles, is preferred in process modelling and applied research. However, its effective use heavily depends on constitutive or closure relations. Indeed, various empirical or arbitrary treatments have to be employed to describe the solid flow in a BF[7-9]. The discrete approach can overcome this problem producing information that can lead to better understanding of the fundamentals involved. It has been heavily used in recent studies of various flow phenomena in a BF by different research groups. This paper reviews briefly our work in this area [10-19].

1 Model description

A particle can have two types of motion: translational and rotational, determined by Newton's second law of motion. During its movement, the particle may collide with its neighbor particles or wall at the contact points and interact with the surrounding fluid, through which the momentum and energy are exchanged. At any time t, the equations governing the translational and rotational motions of particle i are

$$m_i \mathrm{d}\boldsymbol{V}_i/\mathrm{d}t = \boldsymbol{f}_{\mathrm{pf},i} + m_i\boldsymbol{g} + \sum_{j=1}^{k_i}(\boldsymbol{f}_{\mathrm{c},ij} + \boldsymbol{f}_{\mathrm{d},ij}) \quad (1)$$

$$I_i \mathrm{d}\boldsymbol{\omega}_i/\mathrm{d}t = \sum_{j=1}^{k_i}(\boldsymbol{T}_{\mathrm{c},ij} + \boldsymbol{T}_{r,\mathrm{ij}}) \quad (2)$$

where m_i, I_i, $\boldsymbol{v}_i$ and $\boldsymbol{\omega}_i$ are, respectively, the mass, moment of inertia, translational and rotational velocities of particle i. The forces involved are: the particle – fluid interaction force, $f_{\mathrm{pf},i}$, which is mainly the drag force for gas – solid flow systems, gravitational force, $m_i\boldsymbol{g}$, and interparticle forces between particles i and j. The torques include the interparticle torque $\boldsymbol{T}_{\mathrm{c},ij}$ and rolling friction torque $\boldsymbol{T}_{\mathrm{r},ij}$. For multiple interactions, the interparticle forces and torques are summed for k_i particles interacting with particle i. Equations to calculate the interaction forces between particles and between particle and fluid can be found elsewhere[6, 10, 11].

The continuum fluid field is calculated from the continuity and the Navier – Stokes equations based on the local mean variables over a computational cell, which are given by

$$\partial\varepsilon_g/\partial t + \nabla\cdot(\varepsilon_g \boldsymbol{u}_g) = 0 \quad (3)$$

$$\partial(\rho_g\varepsilon_g\boldsymbol{u}_g)/\partial t + \nabla\cdot(\rho_g\varepsilon_g\boldsymbol{u}_g\boldsymbol{u}_g) = -\nabla p - (\sum_{i=1}^{k_c}\boldsymbol{f}_{\mathrm{pf},i})/\Delta V + \nabla\cdot(\varepsilon_g\boldsymbol{\tau}) + m\varepsilon_g\boldsymbol{g} \quad (4)$$

where $\boldsymbol{u}$ and p are, respectively, the fluid velocity and pressure; $\boldsymbol{\tau}$, ε and ΔV are the fluid viscous stress tensor, porosity and volume of a computational cell.

The modelling of the solid flow by discrete particle simulation (DPS) is at the individual particle level, whilst the fluid flow by computational fluid dynamics (CFD) is at the computational cell level. Their coupling is numerically achieved as follows. At each time step, DPS will give information, such as the positions and velocities of individual particles, for the evaluation of porosity and fluid drag force in a computational cell. CFD will then use these data to determine the gas flow field which then yields the fluid drag forces acting on individual particles. Incorporation of the resulting forces into DPS will produce information about the motion of individual particles for the next time step. If the motion of fluid (mainly gas in this work) or solid phase can be ignored, the above DPS – CFD approach will be reduced to the DPS or CFD approach.

2 Results and discussion

2.1 Bell – less and bell type at the top

DPS modelling has been used to study the solid flow in a BF top. Fig. 1(a) shows a bell – less Paul Wurth rig for physical experiment and Fig. 1(b) illustrates the corresponding setting for DPS simulation. By properly adjusting the parameters used in the simulation, it can be shown that the trajectories of coke or sinter from the rotating chute can be well reproduced by simulation (Fig. 1(c))[12]. Such work can be extended to examine the burden distribution in the BF top, e. g. the so – called coke collapse or gauging phenomena[13, 14]. Fig. 2 shows the set – up for such a study and a set of typical results. Clearly, the DPS model can be used study the burden phenomena at the BF top. On this basis, the formation mechanisms of gauging can be better elucidated[14].

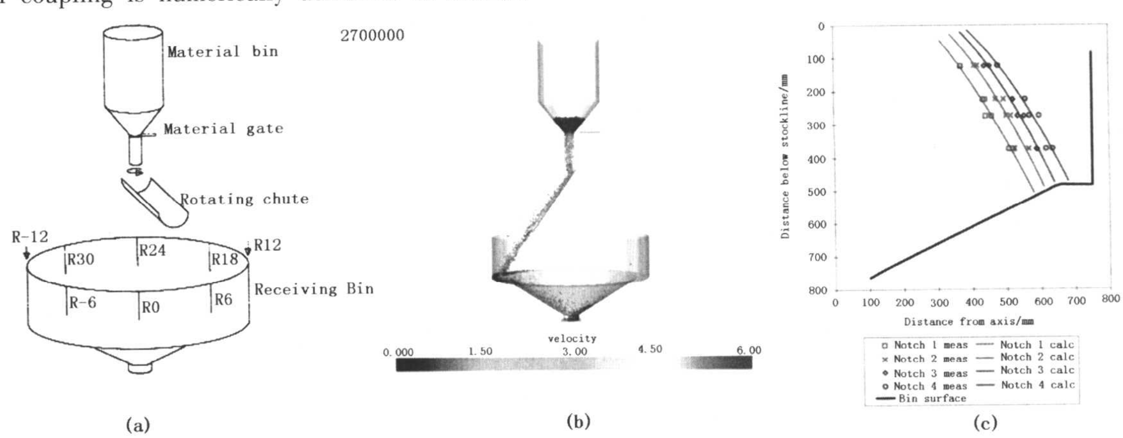
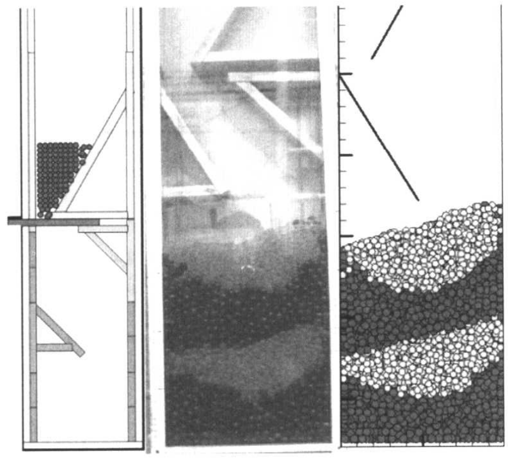


Fig. 1 (a) paul wurth test rig; (b) a snapshot of particle flow from bell-less top; (c) comparison of the measured and simulated trajectories of coke particles

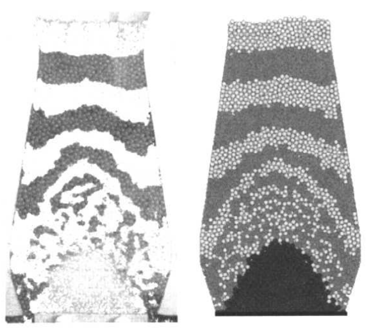


(a) (b) (c)

Fig. 2 (a) set-up; (b) experimental observation (glass beads/wooden ball packing); and (c) corresponding DPS results

2.2 Gas – solid flow in BF shaft

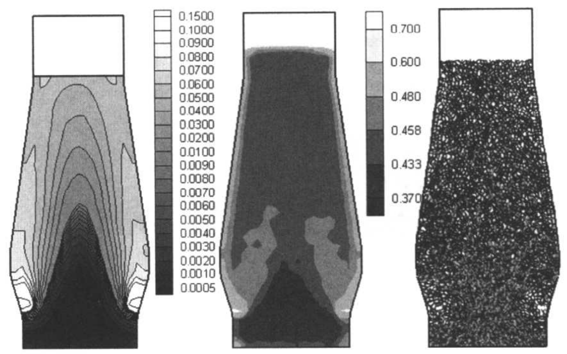
Understanding the descending behaviour of solid particles (coke and ore) within BF is important. It can be shown that the DPS model is a valid technique for this purpose as shown in Fig. 3 [11]. Particularly, the stagnant zone (black region), which forms at the lower central part, is naturally generated by this approach, different from the conventional continuum approach[7-9]. Moreover, microscopic information, such as flow structure (i. e. velocity, porosity, coordination number) and force structure can be generated for further understanding solid flow within BF, as shown in Fig. 4.



(a) (b)

Fig. 3 Solid flow patterns observed in the small scaled BF experiment (a), and in the discrete particle

High solid and gas flow rates correspond to high BF productivity and affect solid flow. This effect can be examined by the DPS – CFD approach [15]. Fig. 5 shows typical results, which confirm that the size of the stagnant zone decreases with increasing solid flow rate, and increases with increasing gas flow rate [3-5].



(a) (b) (c)

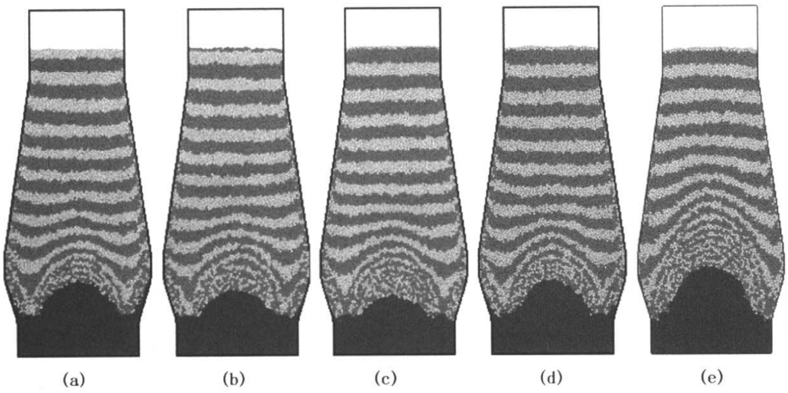
Fig. 4 (a) Time-averaged solid flow field, (b) spatial porosity distribution, and (c) normal contact force structure

The cohesive zone (CZ) is formed due to the softening and melting of ore particles. Its effect on solid flow can be examined under certain assumptions [16]. Fig. 6 shows a set of results for the inverse – V shaped CZ. The positions of ore layers in the cohesive zone vary with time, and the solid flow is transient. Correspondingly, the gas flow is also transient, although the CZ still functions as a gas re – distributor. This transient gas – solid flow would affect the BF operation although it is not explored much in the past.

2.3 Gas – solid flow in BF raceway

Coke combustion in raceways provides heat and reducing gases for the smelting process. Understanding the flow phenomena is important. The DPS – CFD approach offers a useful technique to achieve this goal. As shown in Fig. 7, the approach can reproduce the experimental measurements well [10, 17, 18]. On this basis, simulations have been extended to study more complicated flow phenomena, for example, the hysteretic effect reflected in the pressure drop – velocity relationship (Fig. 8), the effect of capillary and viscous forces induced by liquid phase[6], and the effect of solid pressure (load) and coke consumption [18].

Particle – scale studies can lead to a better know – why knowledge about the gas – solid flow in a raceway. For example, as shown in Fig. 9 (a),



	W_s	Q_g
(a)	0.15	0
(b)	0.3	0
(c)	0.6	0
(d)	0.3	1.93×10^{-2}
(e)	0.3	5.79×10^{-2}

Fig. 5 Solid flow patterns for different gas and solid flow rates Q_g (m^3/s) and W_s (kg/s)

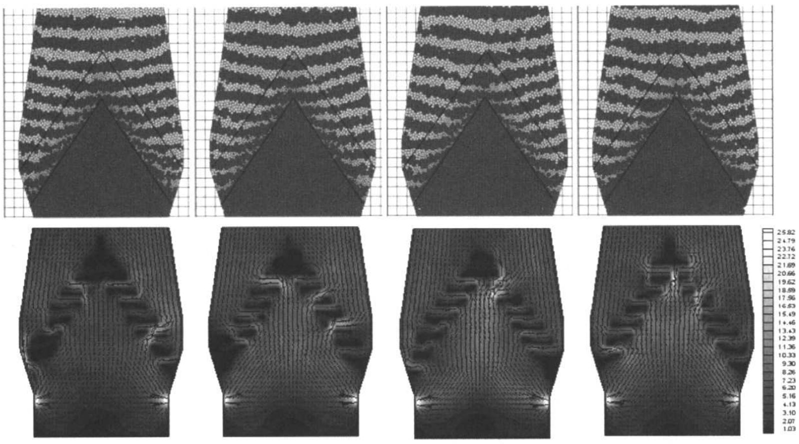


Fig. 6 Snapshots of solid flow patterns (top), and corresponding gas flow field in m/s (bottom) in the cohesive zone

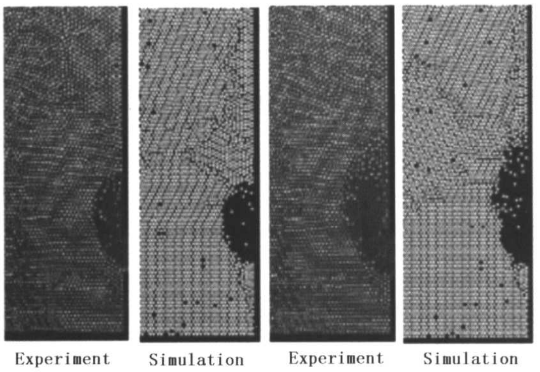


Fig. 7 Formation of a cavity: measured vs simulated when gas velocity is 25 (left) and 26 (right) m/s, respectively

large inter-particle forces occur mainly around the raceway boundary and propagate into the particle assembly in a complex way. The results suggest that the breakage of particles or generation of fines could happen in the raceway and adjacent regions and hence provide a good reason why, both in blast furnace operations and laboratory experiments, coke fines are found around the raceway boundary. On the other hand, Fig. 9 (b) shows the distribution of the fluid drag force, where large fluid drag forces are found at the raceway roof, demonstrating that the raceway roof is mainly supported by the fluid drag force.

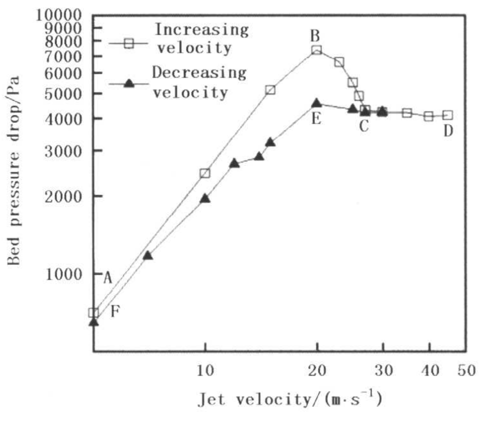


Fig. 8 Bed pressure drop versus gas velocity when gas is injected laterally into a packed bed (Fig. 7)

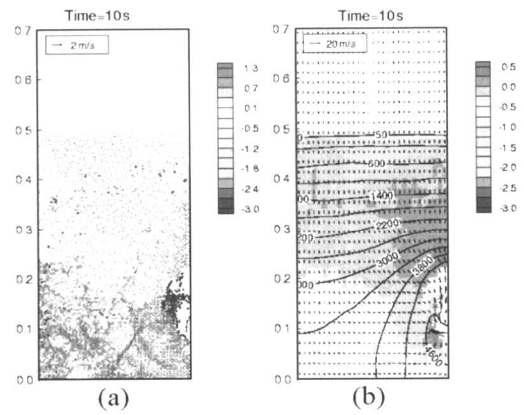


Fig. 9 Typical results when gas velocity is 26 m/s: (a) particle velocity and inter-particle force; (b) gas velocity, isobars and fluid drag force (all forces are ratios to gravity)

Coke combustion and associated solids movement around the raceway are simulated by extraction of particles from the bottom of the bed, and the effect of bed height or solid pressure can be considered by imposing a downward force on the top layers of particles in the bed [18]. As shown in Fig. 10, depending on the load or solid extraction, the bed can transit from a fluidized bed to a fixed bed or vice versa. The results clearly show that the formation of raceway depends on a range of variables, which should be quantified carefully.

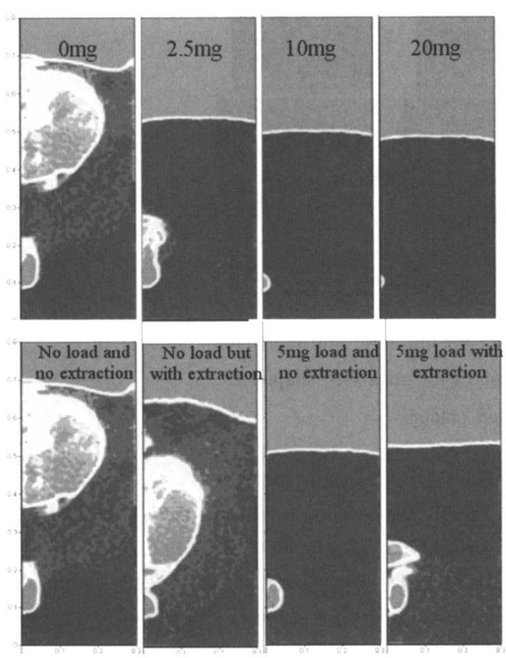


Fig. 10 Effect of load force on raceway size (top), and effect of solid extraction from raceway on the solid flow pattern with or without load conditions (bottom) when gas velocity is 30 m/s

2.4 Solid flow in BF hearth

The flow of particles in hearth is driven by both the downward gravitational and upward buoyancy forces. This can be demonstrated from the simple experiment shown in Fig. 11. The solid flow patterns are strongly affected by the level of liquid and the position of discharging hole due to the upward buoyancy forces [19]. The DPS can reproduce the results satisfactorily. When extended to BF simulation, as shown in Fig. 12 where particles are coloured depending on their resident time in the hearth, it can be demonstrated that coke – free space is formed at the hearth corner because of the strong buoyancy force. The behavior of the sharp change in residence time for particles adjacent to the white particles is similar to that for a quasi – stagnant zone. Therefore, the zone occupied by the white particles largely represents the so – called deadman in a BF.

Such simulation can be extended to a "full" BF operation which involves two types of materials (coke and ore) and a CZ [16]. The results in Fig. 13 confirm that the solid flow is affected by the liquid level which is related to BF casting operation, in addition to other variables such as the gas and solid flow rates.

3 Concluding remarks

The DPS – CFD approach has been employed to study various flow phenomena in a blast furnace from the top burden distribution to solid flow in the hearth. The results obtained thus far clearly indicate that this approach is able to capture the main features of the complex BF flow phenomena, and can generate particle scale information for better fundamental and process understanding. Future effort is to extend this approach to model the phenomena not only related to flow but also heat and mass transfer, and hence develop a DPS – based process model for practical application.

Acknowledgement

The authors are grateful to the Australia Re-

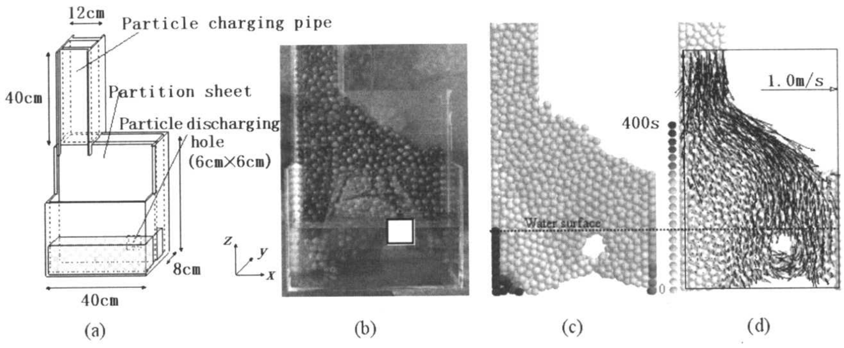


Fig. 11 (a) Experiment set-up; (b) flow patterns from experiment; (c) flow patterns from simulation using DPS; and (d) solid velocity field

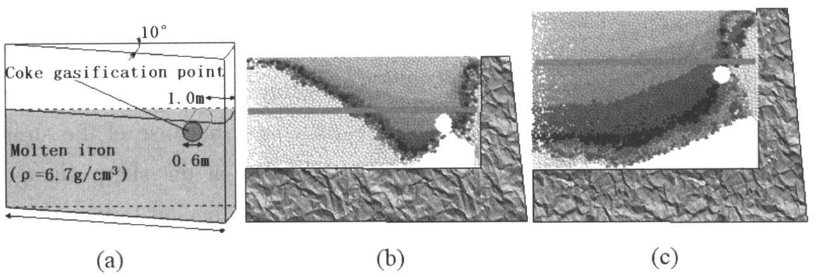


Fig. 12 Geometry of simulated hearth section (a); spatial distribution of residence times of particles with shallow hearth (b) and deep hearth (c), where the red line represents the liquid level

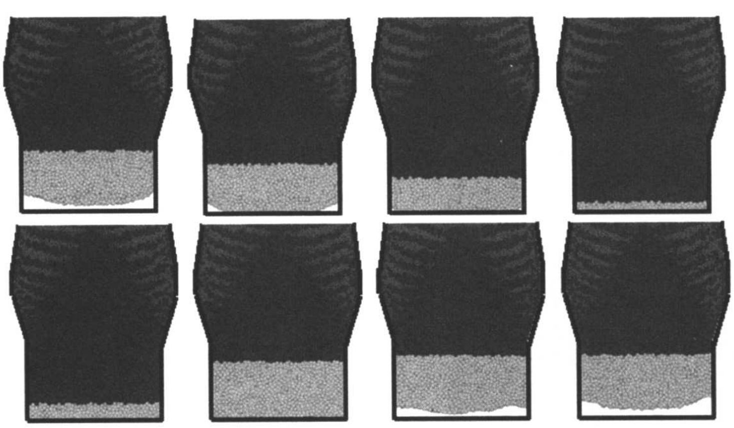


Fig. 13 Snapshots of solid flow patterns with liquid level decreasing (top) and increasing (bottom) in the hearth with time interval 2.4 s for a furnace with inverse-V shaped C at different liquid level (green colour)

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COREX® and FINEX® Technology——Process Updates 2006

D. SIUKA, C. BÖHM, K. WIEDER
(Siemens VAI)

0 Introduction——Factors supporting COREX® technology

Currently, an increased interest in COREX® technology can be seen as a result of a number of factors which have been confirmed during the past years:

(1) All COREX® plants operate above nominal capacity, at high availabilities and produce high-quality hot metal at low consumption rates.

(2) As a consequence of the improved operation, also plant feasibility has increased considerably.

(3) The results of theoretical production-cost calculations have been verified under by operational practice.

In addition to process and the technology improvements, other "external" factors, driven by global development, support COREX® technology:

(1) In most countries environmental-protection measures have gained more importance and are now being implemented.

(2) Due to the lower availability of metallurgical coal and due to higher consumption its price has increased considerably in comparison with "COREX®" coal. As the global reserves of "low-cost-mining metallurgical coal" are being increasingly depleted, a significant price decrease is not expected in the future.

(3) Another highly important factor is the continuing price increase for natural gas. Fig. 1 shows the spot-price development of natural gas according to the New York Commodities Exchange (Henry Hub). These spot prices are only an indication for steel works operator, however, the actual prices for natural gas will increasingly approach these spot prices. As a COREX® plant produces high quantities of a pure gas which could substitute natural gas, this makes this technology extremely attractive in areas where a high natural gas price prevails.

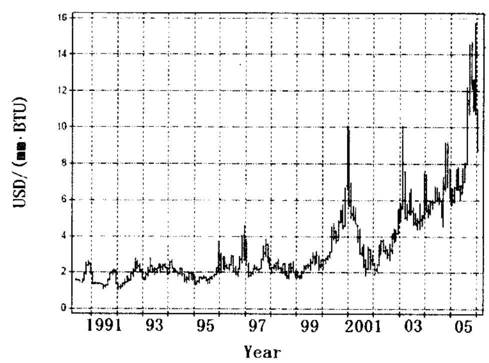

Fig. 1 Natural gas price trend at the Henry Hub

1 Status of operating COREX® plants

1.1 Saldanha Steel, Saldanha Works, South Africa

The highlights of the COREX®/combined direct-reduction (DR) plant at Saldanha Steel during the year 2005 are as follows:

(1) Uninterrupted hot-metal production output of approximately 750 000 t;

(2) Plant availability (calendar time) exceeding 92.5%;

(3) Supply of gas to a COREX®-gas-based DR plant for the separate production of 750 000 t of DRI (direct-reduced iron);

(4) Installation and successful results with the installed Gimbal Top® coal-charging system for a controlled distribution of coal into the melter gasifier. The installation of a Gimbal Top® burden-distribution system for the reduction shaft is planned for the year 2006;

(5) Utilization of more than 95% of all COREX® slag processed in a slag-granulation plant in the cement industry;

(6) Recycling of all generated mill scale in the COREX® melter gasifier;

(7) Utilization of all COREX®, DR-plant, and steel-plant dusts and sludge processed in a sludge-