Modelling of Gas-Slag Flow Behavior in the Ironmaking Blast Furnace: A Review

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ABSTRACT

In the lower zone of blast furnace (BF), slag trickles down through a packed bed of carbonaceous particles in the form of films, rivulets or droplets. During its downward flow, there are significant interactions occurring between slag and other phases, i.e. gas and packing particles. In particular, the interaction between gas and slag is closely associated with the key flow phenomena such as loading, flooding or channelling in the lower zone of the BF. With gas introduced laterally through tuyeres and slag flowing downward from the cohesive zone to the hearth, this interaction varies throughout the lower zone and in the cohesive zone: a) strong cross-flow of gas relative to the slag occurs in front of the raceway, b) counter-current flow of gas and slag occurs in the upper parts of the lower zone and c) both strong cross- and counter-current flow of gas and slag around and within the cohesive zone. These interactions can be linked to furnace irregularities, affecting smooth operation and limiting production. Therefore, understanding the gas-slag interaction and its influencing factors remains critical for BF process control.

In the current review, the physical behaviour and key influencing factors of gas and slag flow are initially examined. Numerical models describing gas and slag flows in a packed bed at micro-, meso- and macro-scopic levels, are reviewed. Each simulation approach has its advantages and limitations, as well as unique assumptions when used in BF process modelling. Applications of these approaches to gas-slag flow in key identified functional zones will highlight the differences between approaches and modelling outcomes. As no single approach can fully address all aspects of gas-slag interactions, an integration of different approaches is considered an effective and beneficial method in providing a more complete understanding of gas-slag flow in the BF process.

INTRODUCTION

In the blast furnace (BF), the impurities (silica and alumina) in iron ore are removed in the form of blast furnace slag through the combination with flux materials such as limestone, dolomite and other slag forming agents. Slag is formed in the cohesive zone (CZ) of the BF process, together with the generation of liquid iron (hot metal). The liquid percolates through the coke in the lower zone, to the hearth. If pulverized coal injection or other solid injection technology is practiced, then at high rates, unburnt coal (or other remnant materials) may leave the raceway region via gas entrainment as a distinct powder phase. Thus, the multi-phases in the lower part of BF interact exist. During slag generation and removal from the furnace, physicochemical characteristics of slag and its interaction with other phases significantly influence BF operation in terms of furnace permeability, hot metal (HM) products quality and productivity, desulphurisation, coke consumption and production efficiency.

In terms of slag properties, different types of slags are usually identified across different regions, such as primary slag in the CZ, bosh slag in the dripping zone, and final slag in the hearth. For smooth operation, the flow behaviour of slag in different regions needs to be understood. In this review, the physical behaviour and key influencing factors of gas-slag flow in the BF are initially examined – this is followed by a summary of the numerical approaches applied to the gas-slag flow in the process. General mathematical formulations are introduced with respect to the approaches used at micro-, meso- and macro-scopic levels. Afterwards, the application of these approaches to gas-slag flow in major regions of interest is discussed in relation to key flow features. Finally, the challenges of modelling of gas-slag flow in the BF process are summarized, with emphasis on model development trends.

PHYSICAL PHENOMENA OF GAS-SLAG FLOW IN THE IRONMAKING BLAST FURNACE

Dissection studies of quenched blast furnaces demonstrate the existence of a CZ where the liquid iron and slag are generated from reduced and melted ferrous materials (Omori, 1987). The generated liquid trickles down through the coke bed to the hearth. During this process, very complex and intensive interactions occur, such as heat and mass transfer between liquid and other phases. From the dissection studies, specific phenomena were identified, including:

- Liquid generated in the CZ passing directly into the dripping zone or interacting with the cohesive layer beforehand, with metal icicles and slag droplets found in the coke slits of Hirohata No 1 and in Mannesmann No 5 BFs.
- Liquid holdup in Chiba No 1 BF was higher in the lower layers of the CZ than in the radially adjacent dripping zone.
- In Kukioka No 4 BF, a dense layer of metal and slag at the lower and back parts of the raceway cavity was found, suggesting that liquid had descended near the wall immediately above and below the raceway and between raceways.

Slag types

As the slag percolates through the coke zone, i.e. from the CZ, through the dripping zone, and to the hearth, slags with distinct compositions are produced e.g. primary slag, bosh slag and final slag. The formation of primary slag with high MnO and FeO content in the CZ is closely linked to the charged ferrous burden materials. As the descending primary slag incorporates lime and the FeO/MnO in the slag is reduced, the primary slag gradually transforms to bosh slag at tuyere level. After absorption of silica from coke ash and unburnt pulverized coal, bosh slag is converted to the final slag. This slag accumulates in the hearth until tapped. The final slag composition is primarily comprised of SiO_2, Al_2O_3, CaO and MgO.

Flow behaviour

Different slag flow behaviours have been identified around the CZ and near the gas inlet (raceway) through different studies, such as under two dimensional experimental conditions (Chew *et al*, 1997), i.e.

- Molten slag percolates through a packed bed as a series of rivulets or drops.
- Slag/iron flow is significantly affected by the cross-flow of air near the gas inlet so that the dry region can be formed.
- Localized upflow of slag, complete filling of local void, and flooding may occur in the CZ, where strong gas flow and gas-slag interaction exist.

Influencing factors

The complexity of slag flow in the lower part of the BF is affected by these different slags, as well as zone-specific phenomena in the different flow regimes and the different phases states. These are influenced by various factors, including:

- Physical and chemical properties of slag which are functions of slag composition that changes during slag flow.
- Interactions with other phases (e.g. coke) including slag wettability, chemical reactions, heat, mass and momentum transfer.
- High temperature properties of ferrous materials and packing property of coke particles.
- Environmental and operating conditions such as temperature, blast volume and slag volume.

NUMERICAL MODELLING OF GAS-SLAG FLOW IN THE IRONMAKING BLAST FURNACE

Various numerical approaches have been used to simulate the complex flow behaviour of gas-slag in the BF. These may be classified into three categories: (1) continuum approach, (2) ‘discrete’ approach, and (3) miscellaneous approach.

Continuum approach

The key features/issues for continuum-based approaches are:

- Phases are generally considered as fully interpenetrating continuum media
- Coupling between phases is represented by constitutive relations and interaction terms
- Sum of volume fractions of phases is unity

- Application is at a macroscopic level; hence suited for process modelling and applied research due to computational convenience and efficiency.

The general governing equations are within the framework of the two-fluid model (Gidaspow, 1994), as given by:

Conservation of mass

$$\frac{\partial}{\partial t}(\varepsilon_i \rho_i) + \nabla \cdot (\varepsilon_i \rho_i \mathbf{u}_i) = S_i \tag{1}$$

Conservation of momentum

$$\frac{\partial}{\partial t}(\varepsilon_i \rho_i \mathbf{u}_i) + \nabla \cdot (\varepsilon_i \rho_i \mathbf{u}_i \mathbf{u}_\mathrm{i}) = -\varepsilon_i \nabla p + \nabla \cdot \boldsymbol{\tau}_i + \sum_j \mathbf{F}_i^j + \varepsilon_i \rho_i \mathbf{g} \tag{2}$$

The effective use of the continuum approach depends heavily on constitutive relations and the momentum exchange between phases. For gas-slag flow in the packed bed, the momentum exchanges between phases, $\mathbf{F}_i^j$, are mainly empirically based. A summary is provided in Table 1, for gas-solid (G-S), gas-liquid (G-L) and liquid-solid (L-S).

TABLE 1 – Empirical correlations for the interaction forces between phases

	Interaction forces	References
G-S	$\mathbf{F}_g^s = -\mathbf{F}_s^g = -\left[150\mu_g \frac{a_{gs}^2}{36\varepsilon_g} + 1.75\rho_g a_{gs} \lvert \mathbf{u}_g - \mathbf{u}_s \rvert\right](\mathbf{u}_g - \mathbf{u}_s)$	(Yagi, 1991)
G-L	$\mathbf{F}_g^l = -\mathbf{F}_l^g = -0.75 C_{d,gl} \frac{\varepsilon_l \rho_g}{\phi_l d_l} \lvert \mathbf{u}_g - \mathbf{u}_l \rvert (\mathbf{u}_g - \mathbf{u}_l)$	(Szekely *et al*, 1979)
	$\mathbf{F}_g^l = -\mathbf{F}_l^g = -\left[150 f_{gl,1} \frac{(1-\varepsilon)^2 \mu_g}{d_s^2 \varepsilon_g} + 1.75 f_{gl,2} \frac{(1-\varepsilon)\rho_g}{d_s} \lvert \mathbf{u}_g - \mathbf{u}_l \rvert\right](\mathbf{u}_g - \mathbf{u}_l)$	(Iliuta *et al*, 2003)
L-S	$\mathbf{F}_l^s = -\mathbf{F}_s^l = -C_{d,ls} \mu_l \lvert \mathbf{u}_1 - \mathbf{u}_\mathrm{s} \rvert (\mathbf{u}_1 - \mathbf{u}_\mathrm{s})$	(Sugiyama *et al*, 1987)
	$\mathbf{F}_l^s = -\mathbf{F}_s^l = -\left[150 f_{ls,1} \frac{(1-\varepsilon)^2 \mu_l}{d_s^2 \varepsilon_l} + 1.75 f_{ls,2} \frac{(1-\varepsilon)\rho_l}{d_l} \lvert \mathbf{u}_l - \mathbf{u}_s \rvert\right](\mathbf{u}_l - \mathbf{u}_s)$	(Iliuta *et al*, 2003)

‘Discrete’ approach

In the ‘discrete’ approach, the phases are described based on the analysis of the motion of individual fluid elements such as small droplets. Hence, the approach can simulate the fluid flow at micro- or meso-scopic levels. To date, the ‘discrete’ approach has been applied to liquid phase modelling in the metallurgical field through the Smooth Particle Hydrodynamics (SPH) (Kon *et al*, 2012;Natsui *et al*, 2015) and Volume of Fluid (VOF) (Jeong *et al*, 2013;Geleta *et al*, 2020;Dong *et al*, 2021a) methods.

Smooth particle hydrodynamics

The key features/issues for the SPH method are:

- A particle approach for modelling incompressible free surface flows at a microscopic level
- The liquid phase comprises a finite number of individual particles
- The motion of each particle is described using the continuity and Navier-Stokes equations, with the particle is tracked by a Lagrangian method
- Computationally, it is extremely demanding.

The basic equations of the SPH model (Kon *et al*, 2012) are given as follows.

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \boldsymbol{v} \tag{3}$$

$$\frac{D\boldsymbol{v}}{Dt} = -\rho\nabla p + \nu\nabla^2\boldsymbol{v} + \boldsymbol{g} + \frac{\boldsymbol{F}_s}{\rho} \qquad (4)$$

The interaction between individual particles is based on the surface tension model (Kon *et al*, 2012). Gradient and Laplacian models are used to discretise the gradient and Laplacian of scalar and vector quantities. The pressure in the model has to be solved based on the derived Poisson's equation. Some efforts have been made to reduce the pressure oscillation, such as the introduction of restricted compressibility in the Poisson equation to make the simulation stable.

The approach has been applied to dispersion, coalescence and distribution of liquid droplets in a packed bed (Kon *et al*, 2012;Natsui *et al*, 2015). However, SPH simulations are still limited to study at a small scale, such as the influence of solid-liquid wettability and viscosity on liquid flow in a packed bed. It is heavily dependent on the calculation of pressure. The effect of gas flow on liquid droplets has not been considered in the simulations.

Volume of Fluid model

The key features/issues for the Volume of Fluid model are:

- Capable of tracking the interface between immiscible phases
- Simulation of steady or transient movement of multi-immiscible fluids with distinct physical properties is possible
- Multi-physics simulations coupled with other physical models such as heat transfer and chemical reactions is feasible
- Computationally expensive, especially for large-scale simulations

The basic equations of the VOF model are given as follows.

$$\frac{\partial \varepsilon_i}{\partial t} + \nabla \cdot (\varepsilon_i \boldsymbol{u}) = 0 \qquad (5)$$

$$\frac{\partial}{\partial t}(\rho\boldsymbol{u}) + \nabla \cdot (\rho\boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho\boldsymbol{g} + S_m \qquad (6)$$

Solution of the volume fraction equation, i.e. Eq. (5), is used to track the interface between the phases. In the momentum equation, S_m refers to the surface tension force, $2\rho\kappa_i\sigma_{ij}\nabla\varepsilon_i/(\rho_i + \rho_j)$, which is used to account for the interaction between the phases. A single momentum equation is solved throughout the domain, and the resulting velocity field is shared among the phases. The physical properties of the mixture such as density and viscosity are phase-volume-fraction-averaged.

The approach has been applied to liquid droplets flow in a packed bed (Jeong *et al*, 2013;Geleta *et al*, 2020;Dong *et al*, 2021b), where studies at a laboratorial scale were carried out. The flow behavior of slag droplets at a particle scale was visualized and investigated in terms of slag properties, holdup distribution and interactions with other phases. Due to the demanding computational capacity, previous investigations were limited to either small scale or two-dimensional studies when VOF is directly used to simulate liquid flow within the interstitial region between packing particles. However, this method has great potential for future application with the rapid development of computer technology. The same applies to the above SPH method.

The VOF model was also applied to simulate liquid flow in the hearth whilst considering the averaged transport equations in the packed bed (Nishioka *et al*, 2005;Guo *et al*, 2006;Merten *et al*, 2023). In this case, an Ergun type of equation was applied to account for the strong interaction between liquid and packing particles (solids) and used for source term (S_m) in the momentum equation. However, the governing equations for the extended VOF model for bulk flow of slag in the packed bed are not consistent in the literature and further development is required.

Miscellaneous approach

Beyond the continuum and 'discrete' approaches, some specific models have been applied to simulate fluid flow patterns e.g. probability (Ohno *et al*, 1988), tube network dynamic (Eto *et al*, 1994) and force balance (Wang *et al*, 1997) models for liquid flow. Rather than treating liquid as a pure continuous medium or 'discrete' elements, these models adopt more flexible methods. For example:

- In the probability model (Ohno *et al*, 1988), the liquid downward flow is determined by distribution ratios/coefficients determined experimentally.
- In the force balance model (Wang *et al*, 1997), liquid flow is treated as discrete droplets or rivulets that percolate through the packed bed. For applications, in a computational cell equivalent to that used in the continuum approach, a force balance is used for the liquid flow. Through this approach, the liquid flow is determined by gravity and drag forces, and the complex packing geometry.

In the last two decades, various comprehensive reviews (Yagi, 1991;Dong *et al*, 2007;Kuang *et al*, 2017) have summarized the formulation, capabilities and application of numerical approaches applied for the slag flow in the BF process. Earlier reviews (Yagi, 1991) mainly focused on the continuum approach, whilst more recent reviews (Dong *et al*, 2007;Kuang *et al*, 2017) focussed on multi-scale approaches. However, there remain many challenges in the development and application of these numerical approaches. As no single approach can adequately address all aspects in the complex BF process, the following sections provide a summary of findings and capabilities of models with respect to features in major functional zones of BF, as well as their potential future development.

NUMERICAL MODELLING OF LOCAL GAS-SLAG FLOW BEHAVIOUR IN THE FUNCTIONAL ZONES OF A BLAST FURNACE

Based on the dissection study of Japanese BF in 1970s, slag generation, and its subsequent downward flow and interaction with gas are linked within the key BF functional zones, (Omori, 1987). Modelling of gas-slag flow will be reviewed in the following sections in terms of the major identified functional zones: cohesive, dripping and hearth zones.

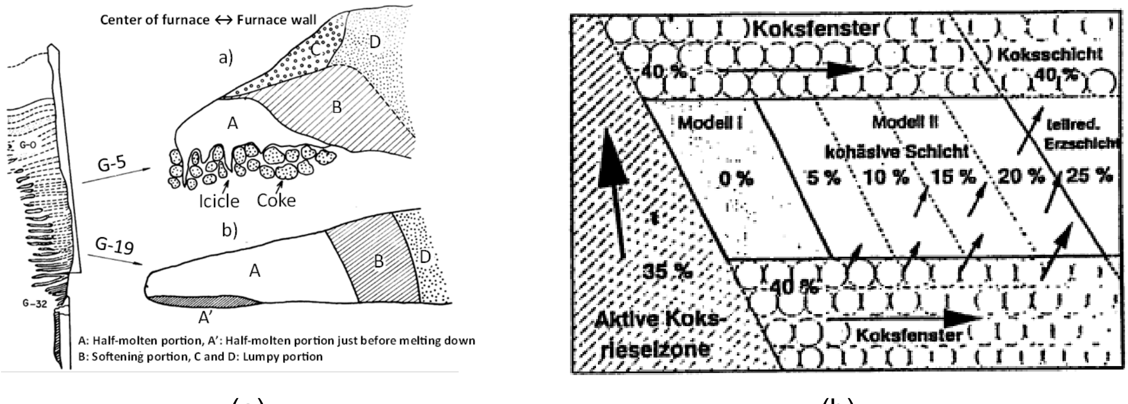
Cohesive zone

The cohesive zone works as a gas distributor and liquid generator with remarkable variations in fluid flow direction, pressure, temperature and species concentration, all of which affect the BF performance, operational stability and productivity.

BF dissection studies showed that the CZ has a layered structure consisting of molten, softening, lumpy and coke-only regions, as shown in Figure 1(a). Iron-bearing materials are gradually transformed from a lumpy through to melt down state. The shape and position of the CZ can change significantly with operational conditions.

In order to better understand this zone, modelling of gas-slag flow was carried out through two ways: (1) CZ sub-model, and (2) global modelling of BF process.

- In the CZ sub-model shown in Figure 1(b), gas tends to flow preferentially through coke-slits. Liquid (primary slag and liquid iron) melts down from ore which is heated by gas passing through the coke-slits. For simplicity, a homogeneous model was applied for slag, iron and iron oxide in the cohesive layer, with an imposed porosity distribution along the horizontal direction of layer, dependent on melting temperature.



(a) (b)

FIG 1 – (a) Schematic showing the internal state of the cohesive zone (Sasaki *et al*, 1977), and (b) model of the cohesive layer (Gudenau *et al*, 1992). Note: Aktive Koksrieselzone – active coke zone, Koksfenster – coke window, Koksschicht – coke layer, Kohäsive Schicht – cohesive layer, teilred Erzschicht – partly reduced ore layer.

- Through global modelling, the CZ is treated either as a mixed region of iron-bearing materials and coke (Sugiyama *et al*, 1987;Austin *et al*, 1997), or discrete layers (Dong *et al*, 2010). Continuum or Miscellaneous approaches were applied for gas-slag flow. However, these simulations were carried out under steady-state or pseudo steady-state conditions whilst ignoring the softening and melting process. It is difficult to understand the impact of transient processes occurring in the CZ – such as softening and melting of iron-bearing materials, phase transformation (e.g. soften-melting, and solidification and flooding phenomena), and chemical reactions, based solely on a global modelling approach. Whilst in global modelling, the CZ region may be defined using solid temperatures or the shrinkage ratio of ferrous materials, in effect, it mainly represented a liquid (slag and liquid iron) source in the modelling.

The prediction of gas-slag flow in the CZ, where there is slag generation and a strong localised liquid flow involving downward, horizontal or even upward flow, remains a longstanding and challenging task.

Dripping zone

The dripping zone is featured by co-existing multiphases such as slag, liquid iron, coke, fine coke and unburnt coal. There are multiple states of each phase including static and dynamic holdup for liquid and powder, as well as complex solids flow regions. In terms of gas-slag flow, unique flow phenomena such as flooding and “dry” areas may be present. Reactions occurring in this zone (including iron carburization reaction and silicon transfer) determine the quality of final hot metal product.

In a numerical sense, the description of this zone is relatively poor. The development of global BF models either ignored the strong interaction between phases or invoked simplifications (Sugiyama *et al*, 1987;Austin *et al*, 1997), especially for liquid flow.

In practice, the interaction between slag and other phases may cause flooding and accumulation – these phenomena are very likely to cause problems in BF operations. In fact, control of the BF process is, in part, constrained by knowledge of these complex phenomena.

In the dripping zone, different models have been proposed to describe the gas and liquid flows in the BF within the framework of continuum and miscellaneous approaches. These include potential flow (Szekely *et al*, 1979;Sugiyama *et al*, 1987), probability (Ohno *et al*, 1988), probability-continuous (Wang *et al*, 1991), tube network dynamic (Eto *et al*, 1994) and force balance (Wang *et al*, 1997) models. Among these, the force balance model is perhaps the most attractive because of its advantages in computation and representation of the relevant physics of liquid flows through a packed bed. As shown in Figure 2, both the liquid dry zone and liquid dispersion can be identified.

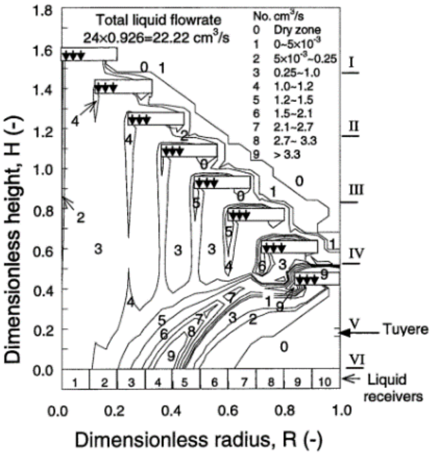


FIG 2 – Predicted liquid flow rate distribution in a simulated blast furnace lower zone (Wang *et al*, 1997). Note that this isothermal simulation is based on the water used at room temperature in the corresponding experiments.

To date, it remains difficult to simulate the division, collection, coalescence and deformation of liquid droplets using the continuum approach. In particular, for the high temperature conditions, the variation of phase properties together with the interactions between phases in relation to reactions and changing interfaces, make simulation more complex. In this respect, the 'discrete' approach has the capability to model and describe coalescence of droplets (Kon *et al*, 2012;Natsui *et al*, 2015;Dong *et al*, 2023). Although the study of the movement of liquid droplets is still at an early stage, the detailed micro-dynamic information provided by discrete techniques will assist in understanding the formation mechanisms of "accumulation" phenomena and the influence of key factors. For example:

- The "icicle" flow of iron under the cohesive zone was highlighted in the discrete simulation
- Good wettability causes less liquid dispersion in the packed bed
- Liquid (slag) viscosity controls the dynamic holdup
- The significant influence of packing structure on the macroscopic flow behavior of slag

Figure 3 illustrates how the distribution of the slag flow path becomes narrower as viscosity increases. Regarding the effect of wettability on the slag flow (Figure 4), a more non-wetting slag (contact angle = 157 deg) flows predominantly around the less permeable (deadman) region (region of smaller diameter particles), with higher slag holdups near the interface. Note that deadman refers to a stagnant zone of coke particles in the center of the lower part of the BF. As the contact angle decreases, slag can flow into the deadman region. In particular, the flow path for the more wetting slag (contact angle = 60 deg) appears stream-like rather than discrete droplets (Figure 4(d)).

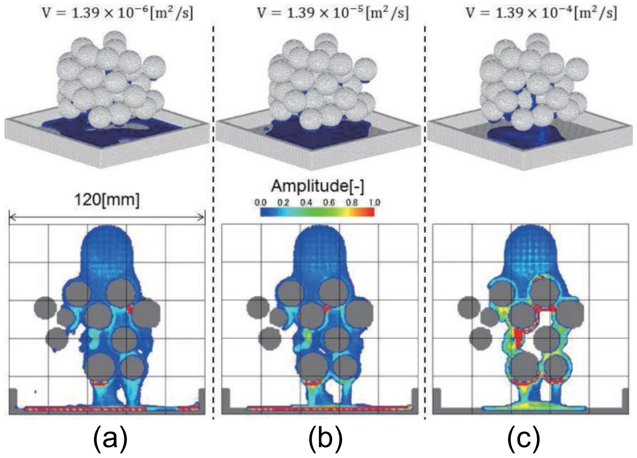


FIG 3 – Effect of viscosity on variation of flow path (Kon *et al*, 2012). Note that assumed liquid properties were used in this isothermal simulation, with surface tension coefficient of water and different viscosities.

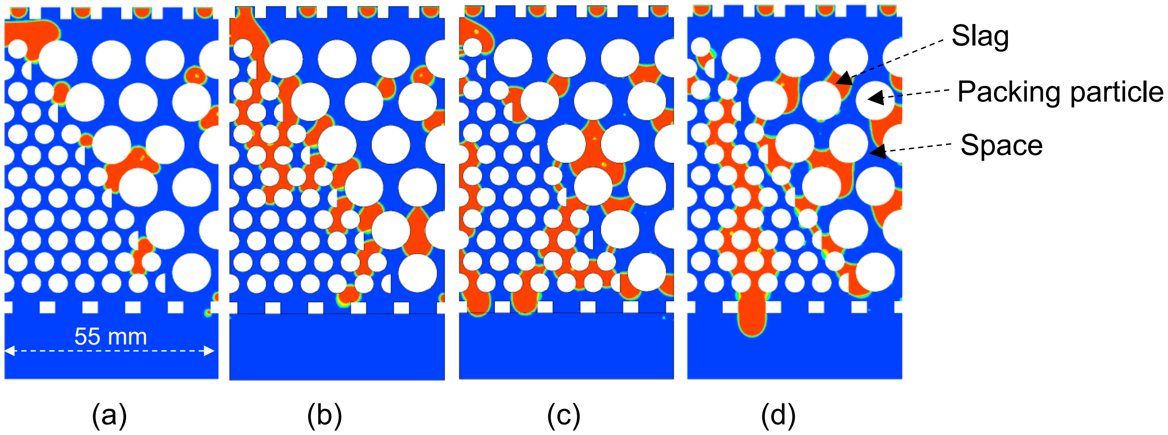


FIG 4 – Effect of wettability on variation of flow path in the packed bed in terms of different contact angles: (a) 157°, (b) 120°, (c) 90° and (d) 60° (Dong *et al*, 2023). Note that the four-component slag used in this simulation consists of CaO 40.7, SiO_2 37.4, Al_2O_3 12.5, MgO 8.8 wt%, and the environmental temperature is constant 1500°C.

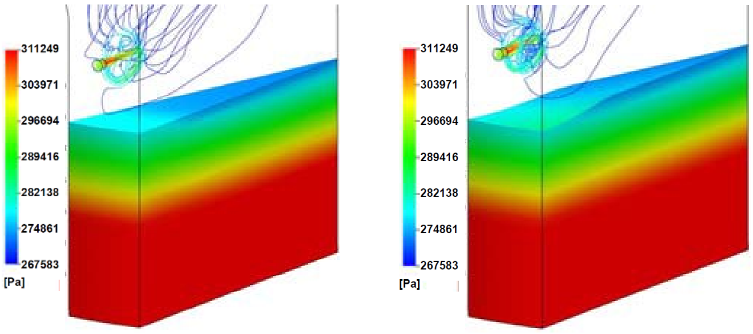
Applying the discrete approach to the dripping zone requires significant computational time due to a very high number of liquid droplets. In the literature, only very limited number of droplets are simulated within a small-scale computational domain (Kon *et al*, 2012;Dong *et al*, 2023). To reliably simulate the liquid flow at a microscopic level, the challenges are evident in terms of computational time. With rapid developments in computational technology, this should be gradually overcome. It is also anticipated that if the strong interaction between gas and slag phases in the lower part of BF is considered in such simulations, heat transfer and chemical reactions can be investigated in detail.

Hearth

Molten liquid products (slag and iron/hot metal) are collected in the hearth, where the large density difference between slag and hot metal leads to two immiscible liquid layers. The coke bed extends to the hearth refractory pad or floats partially or completely in the liquids bath. The flow, temperature and chemistry of liquids significantly influence the refractory wear of the hearth in terms of mechanical/thermal shock and chemical attack as well as the stability of the BF operation, product quality and productivity.

The simulation of coupled liquid flow and heat transfer in the hearth was mainly applied to understand the hot metal flow behaviour (e.g. Panjkovic *et al*, (2002)). There are limited numerical studies (Nishioka *et al*, 2005;Guo *et al*, 2006;Merten *et al*, 2023) on the slag flow and movement of gas-slag interface using an extended VOF model. These mainly focus on:

- Drainage behaviour of slag and hot metal in terms of taphole condition, coke bed permeability and coke size
- Variation of gas-slag interface in relation to different operating conditions such as CZ location, blast condition and deadman properties
- Coupled slag/hot metal flow, heat transfer and chemical reaction (carbon dissolution) in the hearth considering intermittent drainage



(a) (b)

FIG 5 – Pressure distribution in liquid versus liquid surface shape: (a) before deformation, (b) after deformation of liquid surface (Guo *et al*, 2006). Note that the slag density used in this isothermal simulation is 2500 kg·m^{-3} and the viscosity is 0.5 Pa·s.

CHALLENGES OF MODELLING OF GAS-SLAG FLOW IN THE IRONMAKING BLAST FURNACE

Based on this review, research and development areas identified for future consideration for modelling gas-slag flow in the ironmaking BF include:

Model development

- Integration of approaches used at different scales such as a continuum approach at the macro-scopic level and a 'Discrete' approach at micro- and meso-scopic levels
- Appropriate volume/time averaging of VOF model for the bulk flow of gas-slag in the packed bed
- Further development of continuum and miscellaneous approaches enabling their application to special phenomena of slag flow such as flooding
- Development of coupled SPH and continuum modelling for gas-slag flow
- Appropriate incorporation of gas-slag and slag-coke reactions in the transient modelling of gas-slag flow in the coke packed bed considering heat transfer and chemical reactions

- Derivation of the constitutive equations for the interactions between slag and other phases such as fine particles and liquid metal

Phenomena understanding

- Transient process of gas-slag flow occurring in the CZ, considering softening and melting of iron-bearing materials, phase transformation and chemical reactions
- Influence of CZ shapes on slag flow, slag properties and subsequent heat and mass transfer in the lower part of BF
- Evaluation of conditions involving solidification and fluidisation of slag within and around the CZ, and operational CZ limitations in terms of coke slit length and cross-sectional area
- Reliable prediction of residence time and distribution of slag in the dripping zone considering the complex operational conditions and coke bed structure
- Quantitative analysis detailing gas-slag and slag-coke reactions on gas-slag flow in the dripping zone, particularly in terms of varying slag composition, surface tension, viscosity and wettability
- Quantitative analysis of hot metal quality control in terms of interaction between slag and hot metal, and slag-metal reaction in the hearth
- Evaluation of flow behaviour in the slag layer and hot metal bath and gas-slag interface variation in the furnace
- Investigation of the effect of liquid (slag/hot metal) flow on the coke renewal in the deadman

The above research and development efforts should provide the basis for furthering the fundamental understanding and practical evaluation on flow behaviour of gas-slag in the lower part of BF.

CONCLUSIONS

Successful operation of a BF under quite different, potentially more critical, conditions (e.g. low carbon consumption, lower quality raw materials) is more likely to be achieved with a more complete understanding of the complex phenomena in the lower part of the furnace. In terms of liquid flow and its interaction with other phases, use of numerical modelling provides an excellent tool for investigating and determining the influence of such phenomena as dynamic wettability and liquid dispersion in the complex bed structure and functional zones – as well, the liquid distribution under high temperature conditions and various liquid properties can be quantified and potentially used for operational design. This review summarizes the current status of gas-slag modelling and highlights the gaps and challenges in terms of model development and phenomena understanding. Although the developments/challenges are quite broad from the fundamental understanding to the process application, the outcome should provide direct guidance for the preparation of raw material and optimized lower zone control.

It is worth mentioning that the slag properties and the interaction between slag and other phases can significantly affect the numerical modelling results. Therefore, generating high-quality high-temperature thermophysical property data in key areas such as interfacial tension/wettability remains a challenge and imperative beyond the numerical modelling work discussed.

REFERENCES

Austin, P R, Nogami, H, Yagi, J I, 1997. A mathematical model of four phase motion and heat transfer in the blast furnace, *ISIJ International*, 37(5):458-467.

Chew, S J, Wang, G X, Yu, A B, Zulli, P, 1997. Experimental study of liquid flow in blast furnace cohesive zone, *Ironmaking and Steelmaking*, 24(5):392-400.

Dong, X F, Jayasekara, A, Sert, D, Ferreira, R, Gardin, P, Monaghan, B J, Chew, S J, Pinson, D, Zulli, P, 2021a. Investigation of molten liquids flow in the blast furnace lower zone: numerical modelling of molten slag through channels in a packed bed, *Metallurgical and Materials Transactions B*, 52(1):255-266.

Dong, X F, Jayasekara, A, Sert, D, Ferreira, R, Gardin, P, Monaghan, B J, Chew, S J, Pinson, D, Zulli, P, 2021b, Numerical investigation of slag flow through a coke funnel analog and packed bed, *Metallurgical and Materials Transactions B*, 52(5):2926-2938.

Dong, X F, Jayasekara, A, Sert, D, Ferreira, R, Gardin, P, Chew, S J, Pinson, D, Monaghan, B J, Zulli, 2023. Slag flow in the packed bed with varied properties and bed conditions: numerical investigation, *Metallurgical and Materials Transactions B*, 54(1):56-69.

Dong, X F, Yu, A B, Chew, S J, Zulli, P, 2010. Modeling of blast furnace with layered cohesive zone, *Metallurgical and Materials Transactions B*, 41(2):330-349.

Dong, X, Yu, A, Yagi, J I, Zulli, P, 2007. Modelling of multiphase flow in a blast furnace: Recent developments and future work, *ISIJ International*, 47(11):1553-1570.

Eto, Y, Takeda, K, Miyagawa, S, Itaya, H, Taguchi, S, 1994. Experiments and simulation of the liquid flow in the dropping zone of a blast furnace, *ISIJ International*, 33(6):681-686.

Geleta, D D, Siddiqui, M I H, Lee, J, 2020. Characterization of slag flow in fixed packed bed of coke particles, *Metallurgical and Materials Transactions B*, 51(1):102-113.

Gidaspow, D, 1994. *Multiphase Flow and Fluidization*, pp 1-8 (Academic Press: San Diego).

Gudenau, H W, Standish, N, Gerlach, W, 1992. Physical conditions in the area of the blast-furnace cohesive zone .2. measuring results and model development, *Stahl Und Eisen*, 112(9):113-119.

Guo, B Y, Zulli, P, Maldonado, D, Yu, A B, 2006. Numerical analysis of gas flow-slag surface interaction in blast furnace, in *Fifth International Conference on CFD in the Process industries*, (CSIRO: Melbourne).

Iliuta, I, Grandjean, B P A, Piche, S, Larachi, F, 2003. Two-fluid model for countercurrent dumped packing-containing columns, *Chemical Engineering Science*, 58(7):1373-1380.

Jeong, I H, Kim, H S, Sasaki, Y, 2013. Trickle flow behaviors of liquid iron and molten slag in the lower part of blast furnace, *ISIJ International*, 53(12):2090-2098.

Kon, T, Natsui, S, Ueda, S, Inoue, R, Ariyama, T, 2012. Numerical simulation of dripping behavior of droplet in packed bed using particle method, *ISIJ International*, 52(9):1565-1573.

Kuang, S, Li, Z, Yu, A B, 2017. Recent developments in the modeling and simulation of blast furnace ironmaking, *Steel Research International*, 201700071.

Merten, H, Wirtz, S, Bartusch, H, Kaymak, Y, Hojda, S, Lin, R, Scherer, V, 2023. Analysis of the impact of carbon dissolution and energy transport on the flow in the hearth of an ironmaking blast furnace by transient CFD simulations, *Thermal Science and Engineering Progress*, 39: 101747.

Natsui, S, Kikuchi, T, Suzuki, R O, Kon, T, Ueda, S, Nogami, H, 2015. Characterization of liquid trickle flow in poor-wetting packed bed, *ISIJ International*, 55(6):1259-1266.

Nishioka, K, Maeda, T, Shimizu, M, 2005. A three-dimensional mathematical modelling of drainage behavior in blast furnace hearth, *ISIJ International*, 45(5):669-676.

Ohno, Y, Schneider, M, 1988. Effect of horizontal gas flow on liquid dropping flow in two-dimensional packed bed, *Tetsu to Hagane*, 74:1923-1930.

Omori, Y, 1987. *Blast Furnace Phenomena and Modelling*, pp 24-30 (Elsevier Applied Science: London).

Panjkovic, V, Truelove, J S, Zulli, P, 2002. Numerical modelling of iron flow and heat transfer in blast furnace hearth, *Ironmaking and Steelmaking*, 29(5):390-400.

Sasaki, M, Ono, K, Suzuki, A, Okuno, Y, Yoshizawa, K, 1977. Formation and melt-down of softening-melting zone in a blast furnace, *Trans Iron Steel Inst Jpn*, 17(7):391-400.

Sugiyama, T, Sugata, M, 1987. Development of two-dimensional mathematical model for the blast furnace: 'BRIGHT', *Nippon Steel Technical Report*, (35):32-42.

Szekely, J, Kajiwara, Y, 1979. A mathematical representation of spatially non-uniform, countercurrent flow of gases and liquids in packed beds - relevance to flow phenomena in the bosh of iron blast furnaces, *Trans Iron Steel Inst Jpn*, 19(2):76-84.

Wang, G X, Chew, S J, Yu, A B, Zulli, P, 1997. Model study of liquid flow in the blast furnace lower zone, *ISIJ International*, 37(6):573-582.

Wang, J, Takahashi, R, Yagi, J I, 1991. Simulation model of the gas-liquid flows in the packed bed, *Tetsu to Hagane*, 77(10):1585-92.

Yagi, J I, 1991. Recent progress in fundamental and applied researches in blast furnace ironmaking in Japan, *ISIJ International*, 31(5):387-394.