Molten Slag Flow in an Ironmaking Blast Furnace – A Mesoscopic Level Investigation

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ABSTRACT

In an ironmaking blast furnace (BF), molten slag and hot metal form in the softening-melting (cohesive) zone and then trickle through the coke packed bed before being discharged from the taphole. During their downward flow, there are significant interactions occurring between liquids and other phases, such as gas and packing particles. Overall, the formation, dripping and discharging of these liquid phases, particularly molten slag, have a significant impact on BF operations in terms of furnace permeability, fuel consumption, process stability, product quality and ultimately, productivity. Hence, understanding the liquid flow behaviour in the BF lower zone is critical for designing optimal operations.

In the current investigation, the flow behaviour of slag droplets was investigated at a mesoscopic level using a combined numerical and physical modelling approach. The interaction between slag and carbonaceous materials was studied using sessile drop wetting experiments, slag flow through a funnel and a high temperature packed bed, and the Volume of Fluid modelling technique. Molten slag flow and counter-current gas-slag flow in the packed bed was investigated in terms of superficial gas velocity, slag properties and packing structure. The gas-slag flow behaviour at a mesoscopic level was numerically visualized, with gas velocity gradually increased up to the flooding point. The strong interaction between gas and slag was uniquely identified, which can cause localized slag flooding as well as gas channelling. Detailed information concerning the effect on slag holdup distribution, residence time and flow patterns of wettability, slag properties and bed structure were obtained. The current investigation highlights the significant role of research at a mesoscopic level in understanding macroscopic slag flow behaviour. Gas channelling, which is a critical phenomenon in a packed bed with counter-current gas-slag flow, is predicted. It can be speculated that significant gas channelling in the BF can inevitably occur prior to operational limits being reached. In the BF process, the formation of permanent gas channelling and large slag rivulets should be avoided to maintain appropriate contact between phases and hence, furnace permeability.

INTRODUCTION

The lower zone of the blast furnace (BF), in particular, the dripping zone, plays a very important role in the furnace productivity, efficiency and stability, as well as product quality (Omori, 1987). In the lower zone, four phases, gas, solid, liquid and powder such as unburnt char, co-exist and interact in many ways. Essentially, liquid iron and slag trickle down through a slow-moving or quasi-stagnant bed of coke particles, while hot gas, unburnt char and other powdered materials, ascend counter-currently to the coke and liquids. In addition, the hot gas exchanges heat with the descending phases and initiates several heterogeneous chemical reactions. Thus, flow phenomena and interactions in the BF lower zone are very complex.

Researchers have undertaken numerous studies, attempting to understand these complex phenomena and interactions, including those related to slag. These include the formation of molten slag in the BF cohesive zone, its flow through the coke packed bed and ultimately, its discharge from the hearth together with hot metal. Some studies carried out using furnace dissections and tuyere-probe sampling, found indefinite shaped slag particles present in the coke bed, possibly indicating that the flow behaviour of slag in the lower zone may vary considerably along radial/vertical directions (Ichida *et al*, 2001). The composition of the initial slag formed can vary depending on the charged materials (sinter, lump ore, or pellets). The initial slag, often referred to as primary slag, can have an iron oxide (FeO) content up to 30%. When slag flows through the coke packed bed, its composition changes further due to the reduction of metallic oxides, and interactions with coke or remnant char mineral matter or the gas phase. The slag composition varies significantly in the lower zone, both radially and vertically. Similarly, the temperature distribution and the coke morphology also vary along the slag flow path.

To understand the molten liquids flow through BF, several studies have been undertaken at the laboratory scale, both at low temperature (LT) (Chew *et al*, 1997) and high temperature (HT) (George *et al*, 2013). Amongst many causal factors, the behaviour and flow of liquids through the coke bed was found to be affected by:

1. Wetting behaviour of the liquids on coke particles (contact angle, θ),
2. Minimum distance between coke particles, and
3. Packing characteristics of coke particles.

Attempts to understand the effects of these factors were studied through the sessile drop experimental technique, HT funnel and packed bed experiments. The wettability can be measured, and is a function of slag composition and the materials it contacts. It was observed in HT funnel experiments that the residual slag exists in the funnel in different forms, such as slag blockage within the funnel or held up below the funnel in terms of different wettability and pore size. Several HT packed bed experiments were reported to simulate the BF lower zone (Ohgusu *et al*, 1992;Husslage, 2004;George, 2013). These studies indicated that slag and hot metal may flow concurrently through the coke/coke analogue bed in a funicular flow where slag envelopes the hot metal. The liquid flows in rivulets and visits a limited number of possible flow paths/channels. For flow to occur, a critical hydrostatic pressure is required to overcome any resistance to flow. The liquid flow pattern and liquid hold up were affected by the liquid-coke/coke analogue contact angle, liquid chemistry, coke mineral distribution, coke particle sphericity and bed packing density (Husslage, 2004).

Numerically, liquid flow through a packed bed can be modelled at both the mesoscopic level (Natsui *et al*, 2015;Geleta *et al*, 2020;Dong *et al*, 2021a) and the macroscopic level (Sugiyama *et al*, 1987;Wang *et al*, 1991;Wang *et al*, 1997). At the macroscopic level, numerical models were developed within the framework of continuum, such as potential flow (Sugiyama *et al*, 1987), probability-continuous (Wang *et al*, 1991) and force balance (Wang *et al*, 1997) models developed for BF ironmaking, and a two-fluid model approach (Sun *et al*, 2000) applied in the general chemical engineering field. Typically, numerical techniques such as Smooth Particle Hydrodynamic (Monaghan, 1988) and Volume of Fluid (VOF) (Hirt *et al*, 1981) were applied to track the liquid droplets movement through the packed bed at a mesoscopic level. However, for strong gas and liquid flow through a packed bed, the flow behaviour was mainly simulated based on the models developed within continuum frameworks, which generally provide macroscopic, steady-state analysis of flow phenomena, corresponding to experimental or furnace scale conditions, using empirical correlations to characterize the interaction between gas and liquid phases. The constitutive equations for different phases are suitable for a certain application range; however, accuracy diminishes as the application condition approaches or reaches the flooding point.

In this study, an integrated approach that combines HT bench-scale experimentation and furnace-scale computational modelling was applied to study the molten slag flow. The HT experimental studies were carried out to measure the wettability and address liquid flow through the funnel analogues and coke packed beds, and numerical studies were conducted to firstly investigate the slag flow behaviour, considering various bed permeability and more wide-ranging slag properties, and then simulate strong counter-current gas and liquid flow in the packed bed.

NUMERICAL AND PHYSICAL MODELLING APPROACH

The current methods used to study the interaction between slag and carbonaceous materials are presented, including sessile drop wetting experiments, funnel analogue and HT packed bed experiments, as well as VOF modelling technique. Slag flow and strong counter-current gas-slag flow in the packed bed were investigated in terms of superficial gas velocity, slag properties and packing structure.

Physical modelling and experimental set-up

Three experimental techniques were utilised to investigate the slag flow phenomena.

Sessile drop

Sessile drop experiments were carried out in a horizontal tube furnace in an Ar (99.99% purity) atmosphere at 1500 °C. A schematic of the sessile drop experimental setup used to measure the contact angles is given in Figure 1, using the experimental technique (Abdeyazdan, 2016) consisted of four key steps:

1. Pre-assembly of the substrate and alumina tray
2. Temperature stabilization
3. Slag melting
4. Liquid slag addition

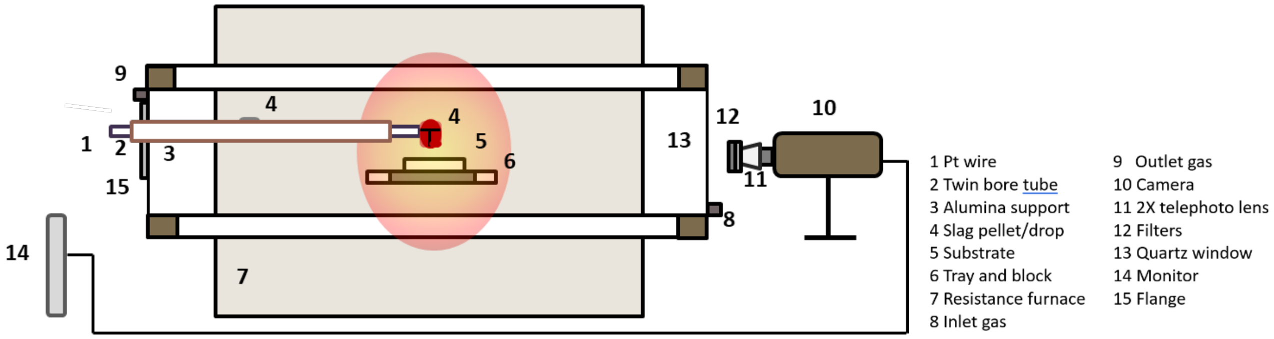


FIG 1 – A schematic of the sessile drop experimental set up (Abdeyazdan, 2016).

Slags with the compositions given in Table 1 were prepared by mixing appropriate amounts of high purity laboratory grade reagents. The slags were primarily chosen to be representative of slags in the lower zone of the blast furnace, to be liquid at the experimental temperature. The properties of slag including surface tension, viscosity and density, were calculated via NPL (Mills, 1991) and Riboud (Riboud *et al*, 1981) models at 1500°C.

TABLE 1 – Slag properties

Phases	Composition, wt%				Viscosity, μ, Pa·s	Surface tension, σ, N·m^{-1}	Density, ρ, kg·m^{-3}	T, °C
	CaO	SiO_2	Al_2O_3	MgO				
Slag 1	40.7	37.4	12.5	8.8	0.264	0.493	2675	1500
Slag 2	43.1	35.9	15.0	6.0	0.303	0.497	2686	1500

Funnel analogue

The funnel experiments were carried out in a vertical tube furnace (Figure 2(a)) in high purity (99.99%) Ar gas at 1500 °C. A slag pellet of ~1.4 g was placed on the funnel as shown in Figures 2(b). The funnels were placed on a graphite holder plate with holes allowing the slag to drip freely into a graphite crucible. The entire setup was fitted within the hot zone of the furnace.

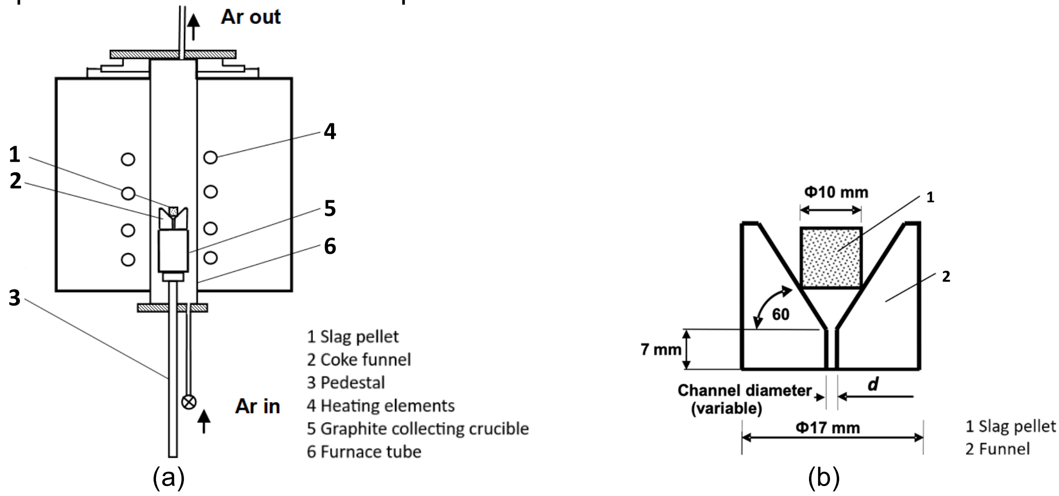


FIG 2 – Schematic diagrams of (a) the furnace arrangement for funnel analogue experiments and (b) a funnel and the placement of a slag pellet (George, 2013).

Packed bed

Packed bed experiments were carried out in a vertical tube furnace under high purity (99.99%) Ar atmosphere at 1500°C. A schematic of the experimental set-up used is given in Figure 3. The slag addition rate was set to 3.3 g min^{-1} and Ar flow rate was 0.5 L min^{-1}. A slag particle size range of 250 – 1000 μm was used in the screw feeder. The coke packed bed height was 70 mm. It was made using ~100 g of coke particles of 8 – 10 mm diameter in size. In the experiments, the slag particles were added to the top of the packed bed via a screw feeder. The slag was then melted and passed through the bed, finally collected in a crucible placed on a micro-balance. Note that the valve in Figure 3(a) was connected to a vacuum pump to evacuate the air in the system before being purged with argon.

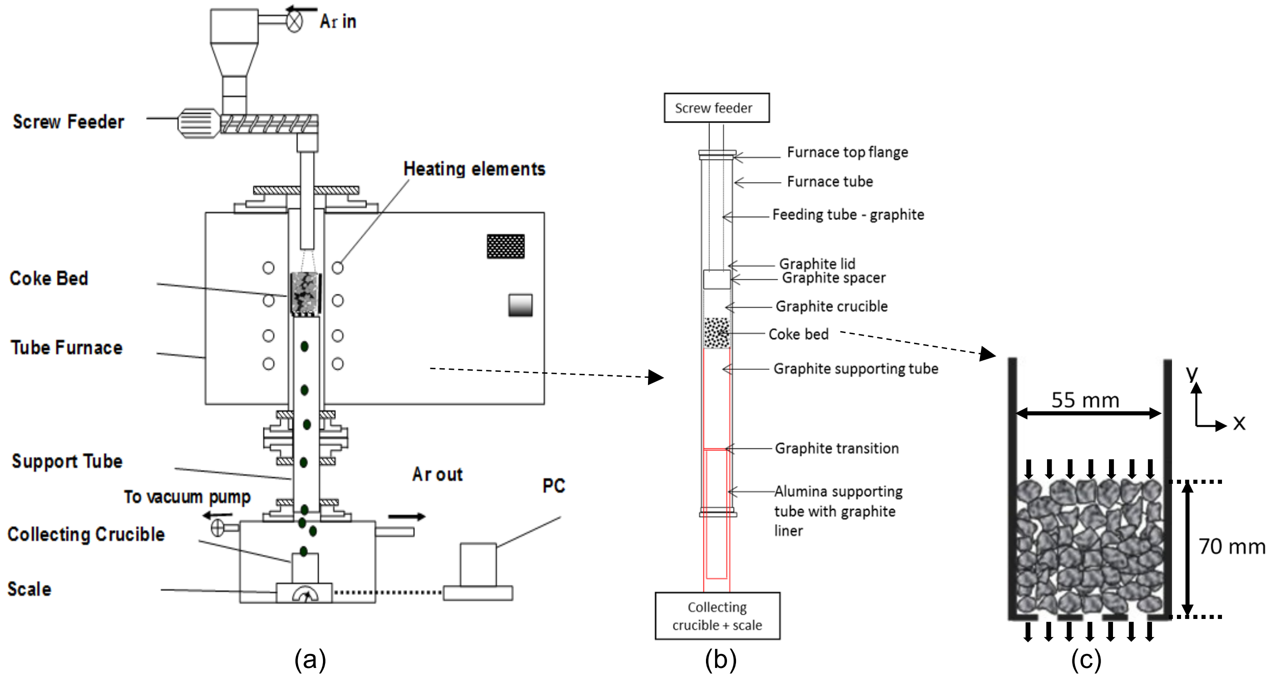


FIG 3 – (a) High temperature packed bed experimental facilities (George, 2013); (b) schematic of the detailed packed bed furnace arrangement; (c) a schematic of the coke bed.

Mathematical modelling and boundary conditions

The VOF method (Hirt *et al*, 1981) was applied to simulate gas-slag flow in packed bed geometries. The simulations were carried out under a two-dimensional slot condition. The general governing equations for mass and momentum transfer were given in recent publications (Dong *et al*, 2021a;Dong *et al*, 2021b;Dong *et al*, 2023). Computations were carried out using the ANSYS-Fluent (v19.1) platform.

The following assumptions were imposed for the mathematical modelling of slag flow:

- Incompressible multiphase flow
- No mass transfer between phases
- No variations in the surface tension coefficient
- Phases are immiscible with a clearly defined interface
- No mass generation
- The system is in a thermal equilibrium
- Phases share the same velocity field
- Laminar flow

The methodologies adopted in the simulation are summarized in Table 2.

TABLE 2 – Methodologies used in the simulation

Items	**Schemes**
Body force	Implicitly treated
Discretization of convective terms	Second order upwind scheme
Gradient used to discretize the convection and diffusion terms	Green-Gauss node-based treatment
Velocity-pressure coupling	SIMPLE algorithm
Calculation of the volume fraction	Implicit formulation
Temporal derivation	First order implicit
Calculation of face fluxes	Modified HRIC

Computational domain and material properties

Two-dimensional simulations were carried out of slag flow based on the HT experimental packed bed geometry (Figure 3). Figure 4 shows the computational domain for slag flow in the different types of packed bed. The inlet, outlet, wall, opening and symmetric lines are highlighted via different colours, i.e. red, green, black, purple and light green colour, respectively.

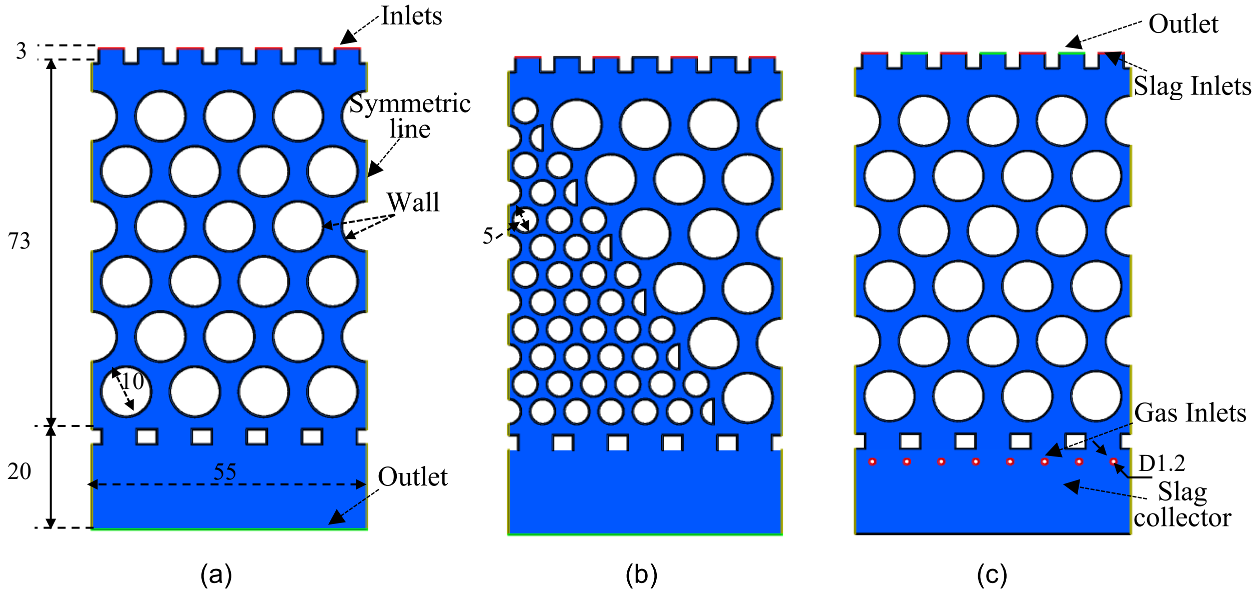


FIG 4 – 2-D computational domain for slag flow in the packed bed (a) base bed, (b) bed with deadman-shaped poor permeability region, and (c) counter-current gas and slag flow in the packed bed (unit: mm).

Slag 1 used in the experimental study was applied in the simulation. The gas properties used in the simulation approximate those under high temperature-high pressure conditions of the lower zone of a BF, i.e. gas viscosity (5.83×10^{-5} Pa·s) and density (0.648 $kg\cdot m^{-3}$).

Initial and boundary conditions

At the beginning of each packed geometry simulation, a slag region was patched near the inlet in the computational domain. The patch was initialized with a volume fraction set to unity for the slag phase and a zero velocity. Each initial condition corresponds to the mass of slag that would flow into the bed within a period of 0.5 s.

The slag is periodically introduced/fed into the packed bed from four inlets at the top. An inlet slag velocity of 5 $mm\cdot s^{-1}$ is used. For the case of counter-current gas-slag flow, gas continuously flows into the bed through the inlets below the packed bed.

For the walls, a no-slip boundary condition was imposed for the gas and slag velocities. A pressure outlet boundary condition was used.

RESULTS AND DISCUSSION

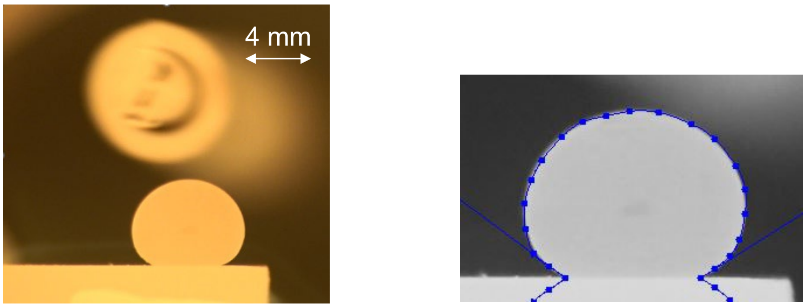
The typical experimental and numerical results are given in this section covering the measured contact angle, flow through the funnel analogue and packed bed, and counter-current gas-slag flow.

Experimental observation and measurement

Sessile drop

Sessile drop experiments were used to measure the contact angles of slags on graphite or coke. As an example, Figure 5(a) shows the original image captured from the recorded video during the experiment using Slag 1 and graphite substrate. Contact angles were then measured using Image J 1.48v image analysis software with DropSnake plugin. An example of the contact angle measurement using Image J is given in Figure 5(b). The measured contact angles for Slags 1 and 2 on graphite substrates are 159 deg and 157 deg, respectively, which are average values based on the time series results.

Sessile drop experiments allow characterization of contact angle and the general interaction behaviour between the molten liquids and solids. Specifically, the contact angle values and key experimental observations will be used for the analysis of the interfacial mechanisms of liquid-solid interactions under representative BF conditions and subsequent numerical simulation.



(a) (b)

FIG 5 – Depiction of contact angle measurement: (a) original image captured from video, and (b) drop analysis using Image J software with DropSnake plugin.

Funnel analogue

Theoretically, the flow of liquids through a coke packed bed will be strongly affected by the gaps or the equivalent diameter of channels between coke particles. At the laboratory scale, the critical pore diameter for liquid flow in this study is investigated using funnel analogues with different neck diameters that approximate to the effective pore diameter between coke particles.

As an example, Figure 6 shows the blocked liquid flow behaviour in coke funnel with a funnel neck diameter of 4.5 mm. The critical funnel neck diameter, as defined by the neck diameter at which point no slag flowed, was determined. In this case using Slag 2, the critical funnel neck diameter was between 4.5 and 5 mm. The blockage phenomena for a highly non-wetting slag is similar to the previous studies (George, 2013), where the near-spherically shaped slag droplet can be observed to be easily held up above the channel of funnel if the funnel neck size is small.

These experiments provide the critical neck diameters associated with the onset of flow through the funnel. In general, slag flow is affected by the slag properties (such as composition, interfacial tension, viscosity) and properties of the carbonaceous matter (ash/mineral content, roughness, porosity, carbon structure). These factors then determine whether the slag can enter the channel and thereby the critical pore diameter.

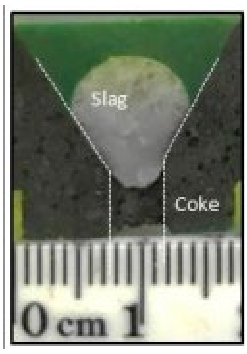


FIG 6 – Blocked slag droplet in coke funnels with a pore neck diameter of 4.5 mm.

Packed bed

Packed bed experiments were carried out to understand the slag flow behaviour and holdup distribution. As examples, two experimental results are given in Figure 7.

The drain curves show a “step-like” characteristic. It was not clear whether the presence of the steps represented stochastic flow in the bed, or an experimental artefact associated with the different packing structures around the crucible outlets (holes), number of outlets and packing properties. Additional experiments were carried out to investigate the effect of those properties on the appearance of steps. However, it was found that the steps remained despite varying the abovementioned properties.

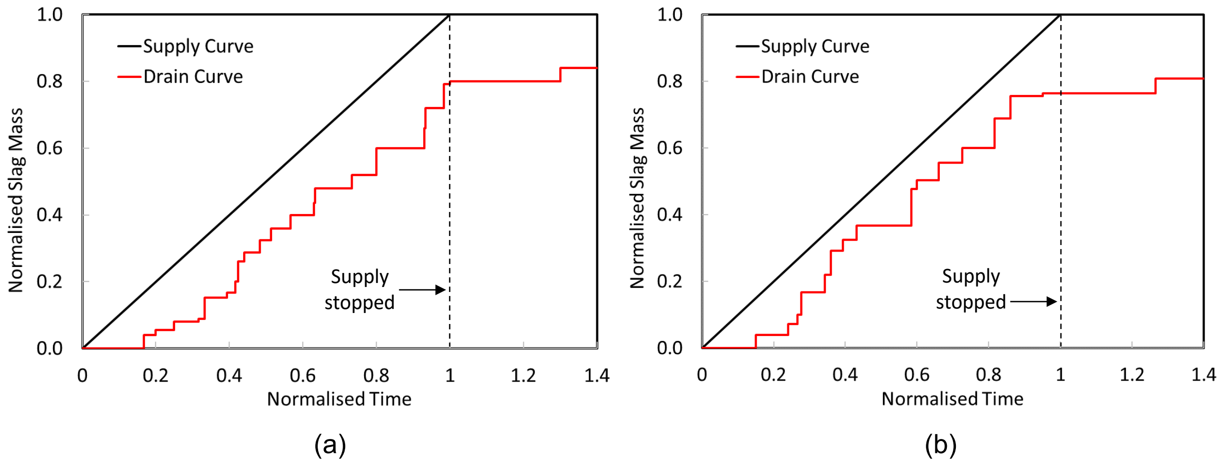


FIG 7 – Supply-drain curves of selected packed bed experiments of (a) Slag 1 and (b) Slag 2.

To further investigate the cause of these steps, a two-dimensional modelling for Slag 1 was carried out. The detailed numerical investigation of the slag flow field showed that step changes in the drain curve are determined by the extent of slag accumulation within the interstitial space among the particles packed, which is closely related to the pore size, the shape and relative positioning of the particles, and slag properties i.e. they were not an experimental artefact but represent something fundamental about the character of the liquid flow. The features of the numerical modelling were detailed in the subsequent section.

Numerical simulation of slag flow in the packed bed

Slag flow in the base bed condition

A two-dimensional simulation for the base bed condition (Figure 4(a)) was carried out of slag flow in the HT experimental packed bed geometry, using a Cartesian coordinate system. The packing particles were assumed to be spherical and evenly distributed in the bed with a bed porosity of 0.51.

Figure 8 shows the transient simulation results at 0, 6, 12, and 18 seconds, respectively. As the slag trickles through the bed, some individual slag droplets are observed to pass through the bed; however, most droplets experience coalescence and break up before exiting the bed. The droplets cannot maintain their spherical shapes after coalescence and easily deform and fill into the pore space between particles, causing local slag accumulation.

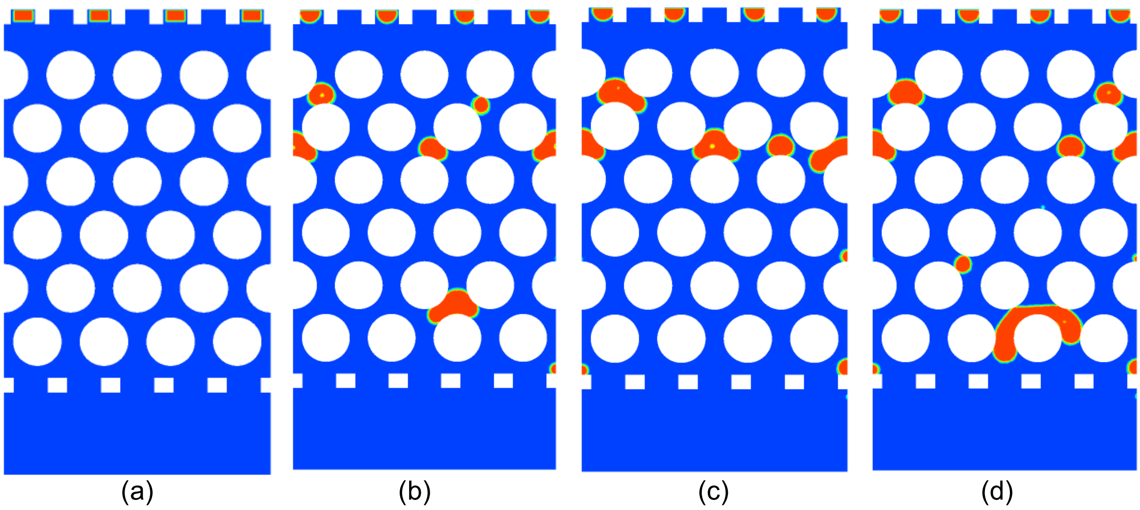


FIG 8 – Simulated slag flow in the base bed condition at different times: (a) 0 s, (b) 6 s, (c) 12 s, and (d) 18 s. Note that Slag 1 was used.

Based on such simulation results, supply–drain curves shown in Figure 9 can be generated. The black and red line in Figure 9 refer to the supply and drain curves, respectively. Compared with the supply curve, there are different step changes in the drain curve, which is consistent with experimental observations (Figure 7). The slag flow field in Figure 7 shows that step changes in the drain curve are determined by the extent of slag accumulation within the interstitial space among the particles packed in the specified domain (Figure 4(a)), which is closely related to the pore size, shape of particles, and slag properties.

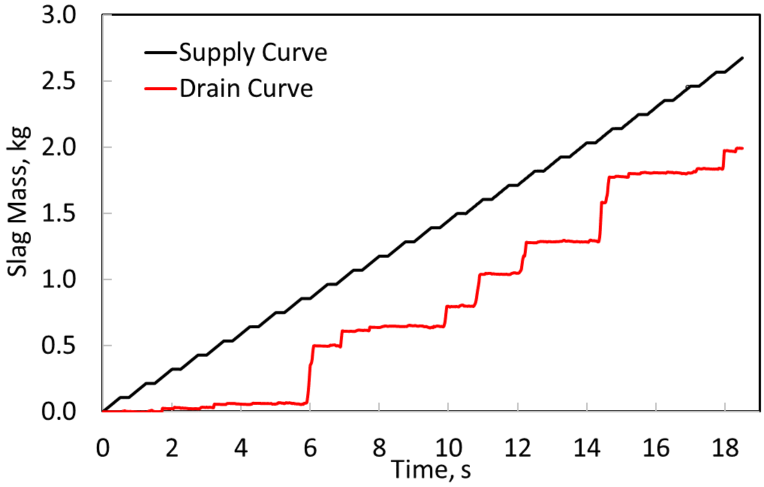


FIG 9 — A supply–drain curve from the simulation based on the base bed condition.

Figure 10 shows the slag flow fields at time t = 18 seconds for different wettability reflected by the varied contact angles in the base packed bed condition. The contact angle changes from 157 to 60 deg characterizes the relation between the acting adhesive and cohesive forces, and reflects reactions that may occur at the coke particle surface. With decreased contact angle, slag holdup in the packed bed increases and longer rivulets can be observed.

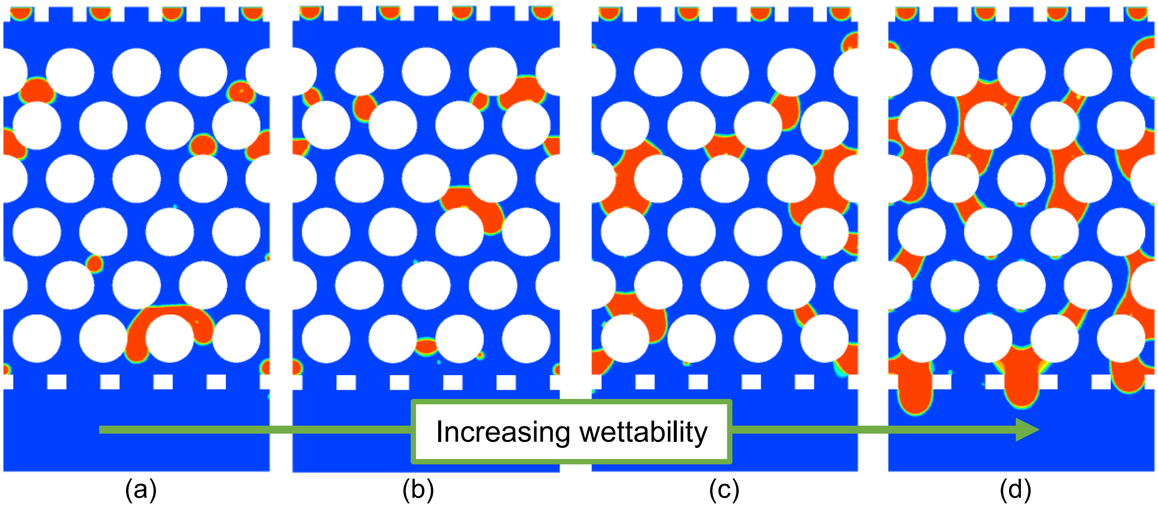


FIG 10 — Simulated slag flow in the packed bed at time t = 18 s for different contact angles: (a) 157 deg, (b) 120 deg, (c) 90 deg, and (d) 60 deg.

Slag flow in the bed with a poor permeability region

To further investigate the effect of a poor permeability region on the slag flow behaviour, a bed with a deadman-shaped region (Figure 4(b)) was considered. In this deadman region, the overall porosity is the same as that in the base bed condition (Figure 4(a)). Figure 11 shows the slag flow fields at 0, 6, 12, and 18 seconds in the bed with deadman-shaped poor permeability region. Most of the slag flows around the deadman region, with higher slag holdups near the interface. Slag flow in a packed bed is closely related to both particle morphology and liquid wettability. It can be expected that flow during the normal blast furnace operation, the region around surface of deadman is critical to the bed permeability and fluid flow.

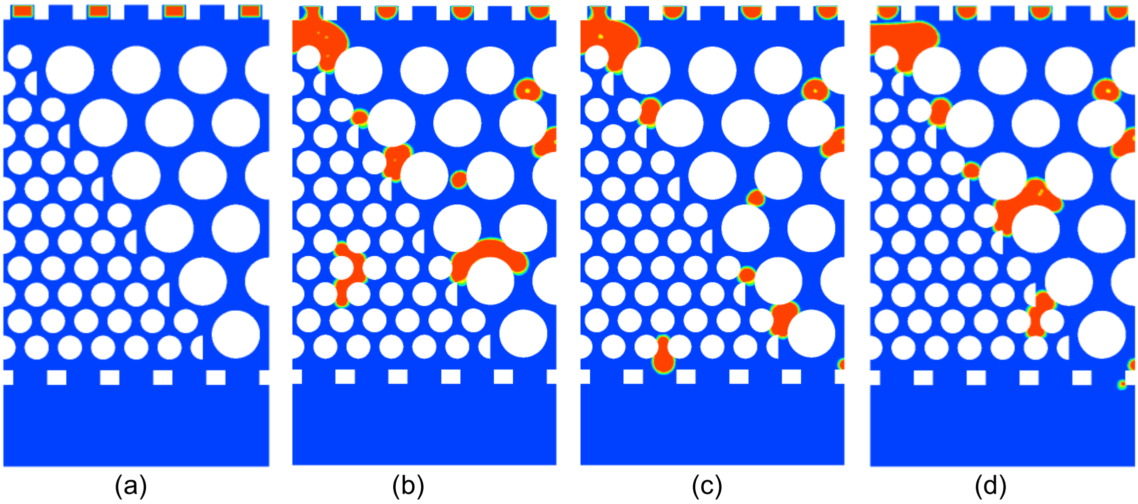


FIG 11 ─ Simulated slag flow in the packed bed with poor permeability region at different times: (a) 0 s, (b) 6 s, (c) 12 s, and (d) 18 s.

Counter-current gas and slag flow in the packed bed

The effect of gas flow on the counter-current gas-slag flow in the packed bed was studied using different gas inlet velocities, corresponding to superficial gas velocities, 0.33, 0.82 and 1.64 m·s^{-1} in the bed, respectively. In the simulation, gas continuously flows into the bottom and out of bed at the top outlets; slag is periodically fed into the bed from the top inlet and collected in the slag collector below the packed bed.

Figure 12 shows the calculated results of superimposed gas velocity and slag volume fraction fields at t = 9.5 s. With increasing gas inlet velocity, local flooding near the top surface of the packed bed becomes more frequent. It can be observed that gas prefers to flow along the paths of lower flow resistance, forming channelling. As the gas velocity increases, the downward flow of slag becomes more difficult and long rivulets has to be formed to generate sufficient hydrostatic pressure to overcome the strong upward gas-slag interaction force.

The local flooding of small liquid droplets near the bed surface can be observed, which is mainly due to relatively large contact areas between gas and slag and less influence of hydrostatic pressure for the small slag droplets.

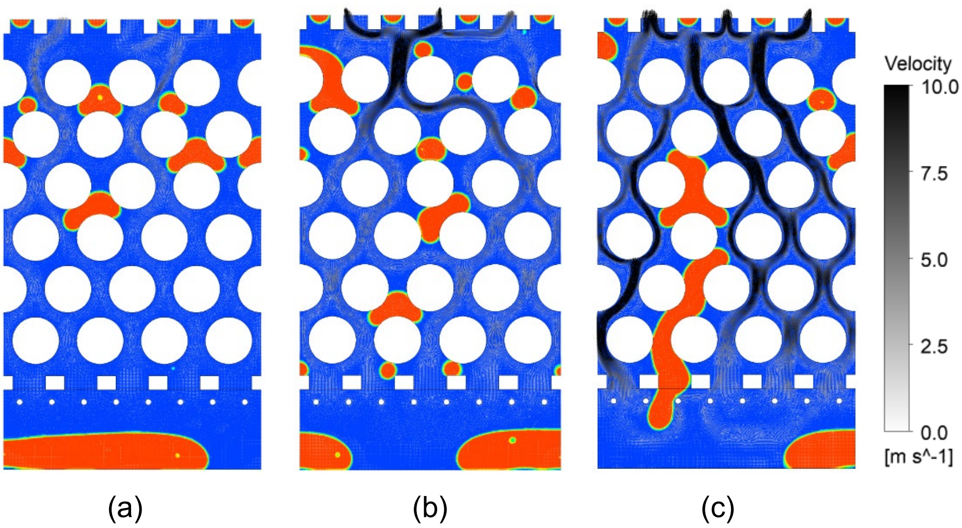


FIG 12 ─ Simulated counter-current gas and slag flow in the packed bed at time t = 9.5 s for different superficial gas velocities: (a) 0.33 m·s^{-1}, (b) 0.82 m·s^{-1}, and (c) 1.64 m·s^{-1}. Note that the legend is used for gas velocity.

In order to understand the flow status of the three current scenarios using the flooding diagram, flooding factor (*FF*), $\frac{U_g^2 a_t}{g\varepsilon^3}\frac{\rho_g}{\rho_l}\eta_l^{0.2}$, and fluid ratio (*FR*), $\frac{U_l}{U_g}\sqrt{\frac{\rho_l}{\rho_g}}$, were calculated based on the superficial gas velocity conditions, given in Table 3. In the calculation of *FF* and *FR*, the overall bed porosity, i.e. 0.51, and the particle size of 10 mm in the base bed were applied. As gas velocity increases from 0.33 to 1.64 m/s, the calculated (*FR*, *FF*) points, No. 1-3 (solid dots), approach the "flooding limit" line. Note that the generation of flooding diagram based on published works was introduced in our previous report (Dong *et al*, 2009). The fluid ratio and flooding factor to achieve the flooding limit was provided in Table 3, with superficial liquid velocity of 0.97 $mm \cdot s^{-1}$. No. 1-3 are highlighted in Figure 13 via solid dots.

TABLE 3 – Flooding factors and fluid ratios based on the current VOF modelling and estimated values

No.	Superficial gas velocity U_g, $m \cdot s^{-1}$	Fluid ratio (-)	Flooding factor (-)
1	**0.33**	0.1895	0.0181
2	**0.82**	0.0758	0.1128
3	**1.64**	0.0379	0.4513

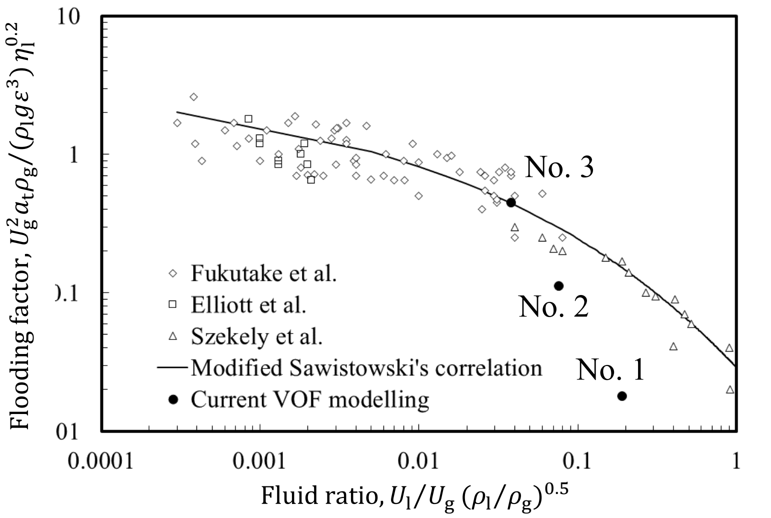


FIG 13 – Flooding data of published works (Dong *et al*, 2009), calculated (*FR*, *FF*) points for cases with different gas inlet velocities.

The comparison between calculated (*FR*, *FF*) points and flooding limit helps interpret the simulation results obtained previously at the particle scale. Observations based on current simulation results show the existence of gas channelling (at the mesoscopic level) even at a relatively low gas velocity (Point No.1). As the points approach the "flooding limit", gas channelling becomes pronounced. Likewise, the local flooding becomes more pronounced near the packed bed surface. At Point 3 on the empirical flooding line, slags still can enter the bed. However, the slag has to accumulate to achieve sufficient hydrostatic pressure to overcome the strong upward gas-liquid interaction force. Evidently, the large rivulets were formed at Point 3 (Figure 12(c)). It can be expected that gas channelling might be the reason for the occurrence of critical points and overall upward liquid flow cannot actually occur. Due to channelling, local flooding and the frequent occurrence of high pressure, the operation can become very unstable, which is consistent with the flooding limit obtained experimentally.

CONCLUSIONS

Numerical and experimental investigation of slag flow in a packed bed was carried out. The wettability between slag and carbonaceous materials can be measured at the laboratory scale. Local blockage and individual droplet flow of slag in the packed bed can be physically identified, which was further verified in numerical studies. A two-dimensional Volume of Fluid modeling technique was applied to simulate gas flow and movement of individual slag droplets. Localized slag flooding and gas channeling caused by the strong interaction between gas and slag were uniquely visualized. Such interactions cannot be ascertained using traditional macroscopic modelling techniques and are also difficult to study under high temperature experimental conditions with gas-slag flow. The current combined physical and numerical approach highlights the significant role of research at a mesoscopic level in understanding macroscopic slag flow behaviour. It can be speculated that significant gas channelling can inevitably occur in the blast furnace prior to operational limits being reached. In the blast furnace process, the formation of permanent gas channelling and large slag rivulets should be avoided to maintain appropriate contact between phases and hence, furnace permeability.

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