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Experimental and numerical investigation into iron ore reduction in packed beds

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HIGHLIGHTS

- Particle resolved heterogeneous reduction of iron oxide in a packed bed.
- Resolved fluid flow e.g. composition and temperature in the void space of a packed bed.
- Coupling between particulate and gas phase for heat, mass and momentum transfer.
- Innovative numerical approach to investigate into packed bed processes
- Analysis of detailed results allows to uncover the underlying physics in packed bed processes.

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ABSTRACT

The objective of this contribution is to investigate into indirect iron reduction in a packed bed on both an experimental and a numerical level. For this purpose experiments of a packed bed of iron ore particles in a laboratory-scale reactor were carried out. Inflow conditions in terms of temperature and reducing gas composition were subject to change and the integral behaviour of the reactor was qualified by measuring the outflow conditions. In particular, the composition of the off-gas was analysed to determine the overall reduction degree of the packed bed. The numerical technique is based on a coupled DEM-CFD approach, in which the iron ore is treated as discrete particles and the flow of reducing gas is described by classical CFD. Each particle is characterised by its thermodynamic state, that is determined by solving one-dimensional and transient differential conservation equations for mass and energy. In conjunction with a reaction mechanism for iron reduction through carbon monoxide, the spatially and temporarily dependent reduction degree for each individual particle is resolved. Integrating over all particles yields the integral behaviour of the reactor. These results were compared to measurements and very good agreement was obtained.

1. DEM-CFD coupled models

Further improvements of computational power and advances in numerical and mathematical modelling of multiphase systems allow us to combine the advantages of two different numerical approaches to build hybrid or the so-called coupled models: a discrete approach like DEM accounts for the solid phase whereas a continuous approach like Finite Element Analysis (FEA) or Finite Volume Method (FVM/CFD) accounts for the gas phase (Natsui et al., 2009; Zhu et al., 2007; Zhou et al., 2010; Adema et al., 2009, 2010). In this way each phase is inherently treated with the most appropriate approach. With these models it is possible to investigate furnace permeability and the influence of the gas flow on the solid descend in much greater detail. Some insights from such simulations are detailed local information about solid and gas flow patterns, local particle velocities, force and stress networks of the solid feedstock which can then be used to evaluate the shape of the cohesive zone or the residence time or temporal history of individual particles. Further it can be investigated how disturbances for example in the raceway influence the symmetry inside the furnace or the stability of the solid flow patterns.

In order to study the influence of the gas flow Adema et al. (2009, 2010) use a slot type model of a lab scale blast furnace similar to the one by Zhou et al. (2005). The entire furnace diameter is considered and periodic boundary conditions are used. They compared isothermal, incompressible DEM-CFD simulation

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for two different gas flow rates. Results show that due to the lift created by the gas flow void space in the bed and thus permeability is increased when gas flow rate is increased. In accordance with findings by Nouchi et al. (2005) the bed is supported by a force network resting below the belly of the reactor. An increase in gas velocity also reduces stresses on the particles located in the force network. Based on the observed loosening of the bed the layered structure is changed on the centre axis of the furnace in favour of a pellet free, coke only region. Lower compressive stresses allow the smaller and sphere shaped pellets to escape into available voids thus effectively shifting them towards the periphery. These pellet free regions due to the larger size and non-spherical shape of the coke particles cause a higher gas permeability just like the region close to the furnace wall. Thus in these regions higher volume flow rates are prevailing which cause higher lift on the burden. Accordingly the descend of the feedstock is decelerated in these regions.

Zhou et al. (2010) extended their DEM model by an isothermal CFD approach for the gas phase. A blast furnace slot model of 4, 5 m in height with coke particles of 40 mm and pellets of 30 mm in diameter. Pellets are allowed to shrink and disappear within the predefined cohesive zone. The shape of the latter can be chosen to be of V-, inverted V- or W-shaped type (Fig. 1). In contrast to the model by Adema et al. (2010) pellet layers inside the cohesive zone are considered impenetrable. Solid flow pattern is in good agreement with findings of other researchers and from the literature. Kurosawa et al. (2012) added shrinking and softening behaviour of particles due to load and material softening within the cohesive zone into their coupled model. In contrast to the model by Zhou et al. (2010) ore layers in a specific region are not per se defined impenetrable but particles are allowed to overlap thus inherently reducing the void fraction of the bed and influencing the gas flow due to their softening. Softening is modelled by changing Young's modulus of the ore particles. They calibrate their model by carrying out numerical compaction experiments for rectangular box of spherical particles but do not present any validation with experiments.

2. Experiments and measurements

Reduction experiments were carried out in a laboratory-scale experimental set-up as shown in Fig. 2.

The experimental set-up includes a muffle furnace, in which the reduction of iron bearing materials took place. A stainless reactor, of which the dimensions are depicted in Fig. 3 for isothermal and non-isothermal reduction, respectively, was supplied with hot reducing gas (total gas flow rate of 8.0 NL/min) that flows axially through the cylindrical steel reactor indicated in Fig. 3. Isothermal refers to a gas flow with a constant inflow temperature, whereas the inflow temperature followed a given profile in time for non-isothermal measurements. An off-gas analysis was connected to the furnace to determine the reduction progress.

A boat, that was inserted into the reactor, contained 45 g and 15 g of iron ore pellets and nut coke, respectively (pellets/nut coke mass ratio 3:1). Pellets were sized 10–12 mm whereas nut coke was 12–14 mm. Both pellets and in particular nut coke were of spherical shape so that an assumed spherical particle shape is justified for the numerical approach. The diameters are varied randomly within the given limits which was also applied to the size distribution for the predictions. Since the inflowing gas contained a significant amount of CO for reduction, CO production

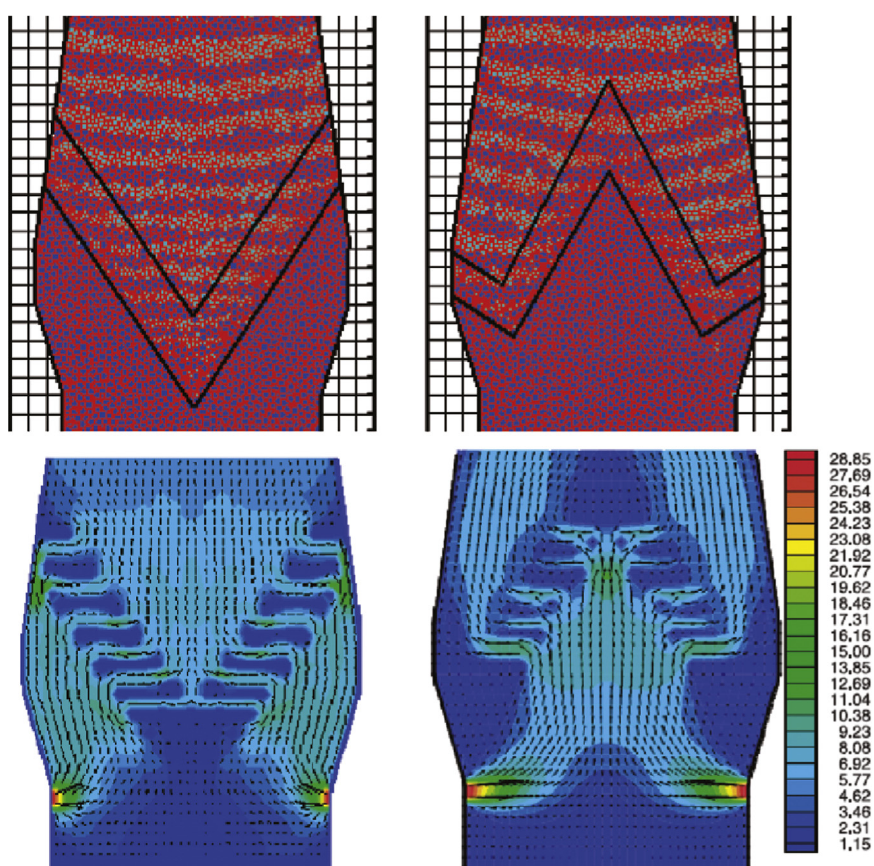

Fig. 1. Layer structure (top) and gas velocity distribution in m/s (bottom) inside the cohesive zone assuming depending on the shape type: V-shaped (left) or W-shaped (right). *Source*: Zhou et al. (2010).