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Effects of the shape and inclination angle of DRI-flaps on DRI distribution in COREX melter gasifiers

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A B S T R A C T

Burden distribution plays a crucial role in controlling gas flow distribution and achieving the stability operation of the melter gasifier in COREX. This work presents a coupled DEM-CFD study on burden formation and gas injection of a COREX melter gasifier (MG), mainly focusing on the effects of inclination angle and shape of the DRI-flaps. A one-eighth MG was simulated and compared with the experimental results. The burdens were analysed in terms of particle segregation index and particle distribution index. It was observed that the particles were unevenly distributed in the circumferential directions. This phenomenon was further enhanced with decreasing flap inclination angles as the burden stream became wider and more separated with decreasing inclination angle. To reduce the uneven distribution of particles, flap shapes were changed. It was observed that the thickness of burden piles was proportional to the area of the flaps. The Arc-shape flap, with a medium size of cross-sectional area, was able to control the uniform distribution of DRI particle and formed a uniform pressure distribution in the circumferential direction. The study shows the importance of flaps to maintain the uniform pressure distribution in the circumferential direction of burden beds for stable operation of the melter gasifier.

1. Introduction

With increasing pressure from diminishing coking coal resources and strict environmental regulations, extensive efforts have been undertaken to develop alternative processes for iron making to traditional blast furnace such as COREX, FINEX and HIsmelt [1,2]. Among these technologies, COREX is regarded as a cost-effective and environmentally-friendly process because of the removal of the sintering and coking processes [3–5]. It is a two-stage process which consists of pre-reduction in a reduction shaft (RS) and final reduction in a melter gasifier (MG). In the pre-reduction process, lump iron ore, pellet and some additives are fed into the RS, and the iron ore is reduced to the so-called direct reduced iron (DRI) with a metallization degree around 80% [6]. The DRI is then continuously charged into the MG through the DRI-flap distributors and finally reduced to molten iron.

An MG normally consists of eight DRI-flap distributors installed on the dome to spread the DRI particles. After impacting with the flaps, the DRI particles are distributed to the burden surface as a ring. It is observed in practice that the DRI particles are unevenly distributed in the circumferential direction with more DRI particles accumulated in the region between two neighbouring flaps [7]. As the burden distribution directly affects gas flow distribution, heat transfer and reduction reaction rate inside the MG [8–10], the unwished circumferential imbalance has a negative impact to the stable operation of the MG [11,12]. So it is necessary to understand the effects of flaps on DRI distribution in the circumferential direction for optimal design and control of the MG.

In the past, experimental studies have been carried out to investigate the burden distribution in the COREX process [13–16]. For example, Chen et al. [13] experimentally investigated the effect of the DRI-flap angle on the charging law and they observed that the burden trajectory was concentrated with small flap inclination angles and more scattered with large inclination angles. You et al. [15,16] built a small-scale experimental model to study the burden distribution with a mixed charging process. The effects of initial burden profile, charging pattern, burden bed height and burden material type were investigated in terms of the radial ore-to-coal ratio and voidage distribution.

Those experimental studies only presented the macroscopic information about the burden distribution. It is difficult to understand the fundamental laws of burden distribution in microscopic scale and the gas flow distribution. To overcome these problems, the discrete element method (DEM) has recently been used to study the burden distribution and gas flow distribution in blast furnace [17–25], FINEX [26] and COREX [27–35]. Narita et al. [21] simulated the charging process at bell-less top by the DEM model, revealing that the particles flowed decentering in the vertical chute led to the circumferential imbalance in the rotating chute. Kou et al. [31] studied the burden profile and distribution along radius in the upper part of the COREX shaft furnace. You

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et al. [28] investigated the effects of Gimbal distributor angle and rotational speed in the COREX MG on burden profile and structure.

However, no study has been conducted to investigate the effect of DRI-flaps on burden structure and gas flow distribution. This work aims to obtain uniform distribution of DRI particles in the circumferential direction with uniform gas flow through combined CFD-DEM simulations. In particular, the effects of DRI-flap shape and inclination angle on DRI burden distribution and gas flow will be studied. The findings of this work will be useful for the control and optimization of MG operation.

2. Model description

2.1. DEM modelling of particle charging

In the particle charging stage, the effect of air flow can be ignored. So the discharge of DRI particles from the DRI-flap distributors was modelled by the DEM model. In the DEM model, the governing equations for translational and rotational motion of a particle i can be written as

$$m_i \frac{d\mathbf{v}_i}{dt} = \sum_{j=1}^{k_i} \left(\mathbf{F}_{cn,ij} + \mathbf{F}_{dn,ij} + \mathbf{F}_{ct,ij} + \mathbf{F}_{dt,ij} \right) + m_i \mathbf{g} \tag{1}$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{j=1}^{k_i} \left(\mathbf{T}_{ij} + \mathbf{M}_{ij} \right) \tag{2}$$

where m_i, I_i, $\mathbf{v}_i$, $\boldsymbol{\omega}_i$ are the mass, the rotational inertia, the translational and rotational velocities of particle i, respectively; t is the time; k_i denotes the particle number in contact with particle i. The forces involved are: the gravitational force $m_i\mathbf{g}$ and the forces between particles which include the normal contact force $\mathbf{F}_{cn,ij}$ and damping force $\mathbf{F}_{dn,ij}$, and the tangential contact force $\mathbf{F}_{ct,ij}$ and damping force $\mathbf{F}_{dt,ij}$. The equations of the forces and torques used in this model are listed in Table 1.

2.2. CFD-DEM modelling of gas injection

A CFD-DEM model was developed to model the gas injection stage by coupling commercial software packages EDEM® with ANSYS Fluent®. In the model, the simulation of the solid particles by DEM was at the individual particle level, while the gas flow was modelled by CFD was at the computational cell level [29,36,37]. The continuum fluid flow is described by the Navier-Stokes equations, given by,

$$\frac{\partial \varepsilon \rho}{\partial t} + \nabla \cdot (\rho \varepsilon \mathbf{u}) = 0 \tag{3}$$

Table 1
Equations of forces and torques acting on particle i.

Forces and torques	Symbols	Equations
Normal contact force	$\mathbf{F}_{cn,ij}$	$-4/3E^*\sqrt{R^*}\delta_n^{3/2}\mathbf{n}$
Normal damping force	$\mathbf{F}_{dn,ij}$	$-2\sqrt{5/6}\chi\sqrt{m^* K_n}\mathbf{v}_{n,ij}$
Tangential contact force	$\mathbf{F}_{ct,ij}$	$-8G^*\sqrt{R^*\lvert\delta_n\rvert}\delta_t$
Tangential damping force	$\mathbf{F}_{dt,ij}$	$-2\sqrt{5/6}\chi\sqrt{m^* K_t}\mathbf{v}_{t,ij}$
Fluid-Particle drag force	$\mathbf{F}_{p\text{-}f,i}$	$\beta V_i\lvert\mathbf{u}-\mathbf{v}_i\rvert(\mathbf{u}-\mathbf{v}_i)/(1-\varepsilon)$
Torque by tangential forces	$\mathbf{T}_{ij}$	$R^* \mathrm{n} \times (\mathbf{F}_{ct,ij} + \mathbf{F}_{dt,ij})$
Rolling friction torque	$\mathbf{M}_{ij}$	$-\boldsymbol{\mu}_r\lvert\mathbf{F}_{n,ij}\rvert R_i\omega_{t,ij}/\lvert\omega_{t,ij}\rvert$

Where, $1/R^* = 1/R_i + 1/R_j$, $1/E^* = (1-\nu_i)^2/E_i + (1-\nu_j)^2/E_j$, $1/m^* = 1/m_i + 1/m_j$, $\chi = \ln(e)/\sqrt{\ln^2(e)+\pi^2}$, $1/G^* = 2(2+\nu_i)(1-\nu_i)/E_i + 2(2+\nu_j)(1-\nu_j)/E_j$, $\delta_n = [(R_i+R_j) - \lvert\mathbf{x}_i - \mathbf{x}_j\rvert]\mathrm{n}$, $\mathbf{n} = (\mathbf{x}_j - \mathbf{x}_i)/\lvert\mathbf{x}_j - \mathbf{x}_i\rvert$, $\mathrm{V}_{n,ij} = (\mathrm{V}_{ij}\cdot\mathrm{n})\mathrm{n}$, $\mathrm{V}_{t,ij} = (\mathrm{V}_{ij}\times\mathrm{n})\times\mathrm{n}$, $\mathbf{v}_{ij} = \mathbf{v}_j - \mathbf{v}_i + \boldsymbol{\omega}_j \times \mathbf{R}_j - \boldsymbol{\omega}_i \times \mathbf{R}_i$.
E and v are the Young's modulus and the Poisson's ratio. R and G are the radius and the shear modulus, while e, μ_s and μ_r denote the coefficients of restitution, the static and rolling friction coefficients, respectively.

$$\frac{\partial \varepsilon \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \varepsilon \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot (\mu \varepsilon \nabla \mathbf{u}) + \rho \varepsilon \mathbf{g} - \mathbf{F}_{p\text{-}f} \tag{4}$$

where ρ, ε, $\mathbf{u}$, p and μ are the density, void fraction, velocity vector, pressure and viscosity of gas phase, respectively. $\mathbf{F}_{p\text{-}f}$ is the volumetric particle-fluid interaction force in a computational cell, given by,

$$\mathbf{F}_{p\text{-}f} = \frac{\sum_{i=1}^{N} \mathbf{F}_{p\text{-}f,i}}{V_{cell}} \tag{5}$$

where $\mathbf{F}_{p\text{-}f,\,i}$ is the particle-fluid interaction force acting on a single particle by gas (Table 1), N and V_{cell} are the number of particles in a grid cell and the volume of a CFD mesh cell [38–40]. In this work, the air flow was assumed as a laminar flow.

3. Simulation conditions

The simulation conditions were similar to those in our previous experimental studies [7,15,16]. Three particle sizes (5, 8 and 11 mm) were used to represent the particle size distribution. Each simulation consisted of two stages: particle charging and gas injection. Fig. 1 shows the geometrical model of the DRI-flap distributor and the charging process in the DEM simulations. There were two inclined pipes, inner and outer pipes, in the distributor. The flaps were installed at the end of the outer pipe. In addition, the fixed point of the rotary axis of flap was about 25 mm from the inner pipe outlet. The flaps controlled the distribution of DRI particles by adjusting the their inclination angles. The height from the end of the flap to the burden surface is 1690 mm, which was the same as the experimental facility used in the previous work [7]. The effect of burden bed height (similar to the height from the end of the flap to the particle bed surface) was investigated in our previous work [16]. The results showed that the burden bed height had a negligible effect on the burden distribution including ore-to-coal volume ratio, voidage and particle size segregation index. As the DRI-flap distributors and furnace stack were symmetrical in the circumferential direction, a one-eighth furnace stack model with the periodical boundary conditions in the circumferential direction was adopted to reduce computational cost.

In the simulations, DRI particles were generated at the top of the DRI-flap distributor and moved downward in the DRI-flap distributor. In the particle charging stage, an initial bed with the thickness of 40 mm was formed at first, then the DRI particles were charged on the initial packed burden bed after impacting with the flap. The mass flow rate of 0.14 kg/s (Table 2) was adopted in the current study to match the experimental condition [7]. It is noted the particle flow rate may affect the burden profiles, such as particle velocity and burden distribution. For example, the dense flow may have more contacts and collisions between particles, which reduces the particle velocity. However, the mass flow rate of DRI particle was almost fixed in the experiments and actual operations based on the melting rate. Therefore, the mass flow rate was fixed and set as 0.14 kg/s in the simulations.

After a particle burden was formed, the charging process stopped. In the gas injection stage, the gas (air) was injected from the bottom of the burden bed to study the effect of burden structure on the gas flow distribution, as shown in Fig. 1. To ensure that the packed bed was not fluidized, the gas velocity in the inlet was set to 1 m/s, which was less than the minimum fluidized velocity of 3.8 m/s calculated from Ergun equation.

The flaps were crucial to controlling burden distribution and gas injection. Hence, two important flap-related variables, flap inclination angle and flap shape, were investigated in this work. The inclination angle is the angle between a flap and the vertical direction as shown in Fig. 2(a). In practice, the charging of DRI particles in the radial direction is controlled by adjusting the flap inclination angle. In this work, three inclination angles, 10.3°, 15.4° and 19.9°, were selected,