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Particle scale simulation of softening–melting behaviour of multiple layers of particles in a blast furnace cohesive zone

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ABSTRACT

The cohesive zone, where ore particles soften and melt into liquid, plays a significant role in determining the layer permeability and structure, hence the flow of gas and liquid in a blast furnace. In this paper, the softening and melting behaviour of particles, coupled with gas flow and heat transfer, is investigated by means of the combined approach of computational fluid dynamics (CFD) for gas phase and discrete element method (DEM) for solid phase. In connection with the previous experimental study, wax and glass particles are used to simulate ore and coke particles, respectively, and the particles are arranged in different alternative layers in a packed bed to simulate the furnace operation. The effects of different variables such as layer configurations and gas properties on the softening and melting of wax particles are examined. It is demonstrated that the layer thickness and position have an obvious effect on the layer deformation and permeability, and hence gas flow; improved gas flow can be achieved in multiple layer operations. The approach and findings should be useful to the establishment of a comprehensive picture about softening and melting behaviour of particles, and their effect on blast furnace operation.

1. Introduction

In an ironmaking blast furnace, ferrous materials such as lump ore and sinter experience a series of processes such as reduction, softening, melting, and dripping to the hearth. At temperatures between softening (~1200 K) and melting (~1400 K), the so called cohesive zone (CZ) can be formed. CZ was firstly observed in the dissection of Higashida No. 5 blast furnace in Japan [1]. It is generally believed that temperature gradient and permeability in CZ change significantly, and have substantial influence on the blast furnace performance. It is a challenging task to develop a comprehensive understanding of CZ. In particular, the annular layers of ore and coke alternatively exist in the CZ [2]. Such a layered structure of CZ plays a critical role in determining the fluid flow, temperature, and concentration fields [3–6].

Numerous efforts have been made to understand the internal state of CZ using different techniques such as dissection studies, in situ measurements, physical experiments, and mathematical modelling. These methods have their own advantages and disadvantages in investigating CZ phenomena. For example, physical experiments can provide particle scale information [7–11], but lack of ability in connecting microscopic understanding of particles to the macroscopic CZ phenomenon. The continuum approach (e.g. two-fluid model) suffers difficulties in obtaining particle scale information, and the explicit assumption of CZ formation has to be made. Many attempts have also been made to treat CZ as layered structure, such as the MOGADOR model [12] and the sequential solution procedure [4]. These simulations can predict the CZ permeability, and provide an overall picture of blast furnace operation. But the assumptions on CZ position and shape are required. Recently, A discrete approach, e.g., particularly the combined approach of computational fluid dynamics (CFD) and discrete element method (DEM), has been demonstrated as a promising and effective model in generating detailed particle–scale information such as interaction forces, velocity, coordination number and local porosity, and simultaneously presenting the macro-characteristics of gas flow [13], which are key to elucidating the mechanisms governing CZ phenomena.

The CFD–DEM approach coupled with heat transfer has been established in the literature, and successfully applied to study various particle–fluid systems such as fluidised beds [14,15], pneumatic conveyer [16], rotary kilns [17], and coal combustion [18]. Recently, such an approach is used to study blast furnace CZ phenomena [19–21]. For example, by establishing the correlation between Young's modulus and temperature, the particle softening–melting process is naturally coupled with gas–solid heat transfer [21]. The model established in [21] can capture the key softening–melting features of wax layer, e.g. sharp increase and decrease of pressure drop, temperature retard

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Table 1
Components of forces and torque acting on particle *i*.

Forces and torques	Symbols	Equations
Normal elastic force	$\mathbf{f}_{cn,ij}$	$-\frac{4}{3}E^*\sqrt{R^*}\delta_n^{3/2}\mathbf{n}$
Normal damping force	$\mathbf{f}_{dn,ij}$	$-c_n\left(8m_{ij}E^*\sqrt{R^*\delta_n}\right)^{1/2}\mathbf{V}_{n,ij}$
Tangential elastic force	$\mathbf{f}_{ct,ij}$	$-\mu_s\lvert\mathbf{f}_{cn,ij}\rvert\left(1-\left(1-\delta_t/\delta_{t,max}\right)^{3/2}\right)\hat{\boldsymbol{\delta}}_t \quad (\delta_t<\delta_{t,max})$
Tangential damping force	$\mathbf{f}_{dt,ij}$	$-c_t\left(6\mu_s m_{ij}\lvert\mathbf{f}_{cn,ij}\rvert\sqrt{1-\lvert\mathbf{v}_t\rvert/\delta_{t,max}}/\delta_{t,max}\right)^{1/2}\mathbf{V}_{t,ij} \quad (\delta_t<\delta_{t,max})$
Coulumb friction force	$\mathbf{f}_{t,ij}$	$-\mu_s\lvert\mathbf{f}_{cn,ij}\rvert\hat{\boldsymbol{\delta}}_t \quad (\delta_t\geq\delta_{t,max})$
Torque by tangential forces	$\mathbf{M}_{t,ij}$	$\mathbf{R}_{ij}\times(\mathbf{f}_{ct,ij}+\mathbf{f}_{dt,ij})$
Rolling friction torque	$\mathbf{M}_{r,ij}$	$\mu_{r,ij}\lvert\mathbf{f}_{n,ij}\rvert\hat{\boldsymbol{\omega}}_{t,ij}^n$

where R^* is the reduced radius of the particle i and j at the contact point, $\frac{1}{R^*}=\frac{1}{\lvert\mathbf{R}_i\rvert}+\frac{1}{\lvert\mathbf{R}_j\rvert}$, $E^*=\frac{E}{2(1-\nu^2)}$, $\hat{\boldsymbol{\omega}}_{t,ij}=\frac{\boldsymbol{\omega}_{t,ij}}{\lvert\boldsymbol{\omega}_{t,ij}\rvert}$, $\hat{\boldsymbol{\delta}}_t=\frac{\boldsymbol{\delta}_t}{\lvert t\rvert}$, $\delta_{t,max}=\mu_s\frac{2-\nu}{2(1-\nu)}\delta_n$, $\mathbf{V}_{ij}=\mathbf{V}_j-\mathbf{V}_i+\boldsymbol{\omega}_j\times\mathbf{R}_j-\boldsymbol{\omega}_i\times\mathbf{R}_i$, $\mathbf{V}_{n,ij}=(\mathbf{V}_{ij}\cdot\mathbf{n})\cdot\mathbf{n}$, $\mathbf{V}_{t,ij}=(\mathbf{V}_{ij}\times\mathbf{n})\times\mathbf{n}$. Note that tangential forces ($\mathbf{f}_{ct,ij}+\mathbf{f}_{dt,ij}$) should be replaced by $\mathbf{f}_{t,ij}$ when $\delta_t\geq\delta_{t,max}$.

period in wax layer, and the low layer permeability in connection with particle deformation. More importantly, gas flow paths in the fused wax layer can be observed, and it is closely related to the operational conditions, e.g. gas flow and bed configuration. These findings are qualitatively consistent with experimental observations [7,22].

In connection with the previous study [21], the CFD–DEM established and validated for the single layer softening–melting simulation is applied in this work to investigate the CZ behaviour with multiple wax layers. A base case with two wax layers is used to discuss the softening–melting process in detail first, and followed by the examination of effect of different variables. Finally, a case with triple wax layers is investigated to demonstrate the effect of layer numbers on the softening–melting process.

2. Model description

The CFD–DEM approach used for particle softening and melting behaviour has been established in the previous study [21], which gives a complete description of the model. For convenience and completeness, it is briefly given below.

2.1. DEM model for solid phase

The DEM model originally proposed by Cundall and Strack [23] is well established and documented in the literature. Generally speaking, a particle can have two types of motion: translational and rotational. According to Newton's second law of motion, the governing equations for the translational and rotational motions, together with energy governing equation, for particle i with radius R_i, mass m_i and moment of inertia I_i can be written as:

$$m_i\frac{d\mathbf{v}_i}{dt}=\mathbf{f}_{pf,i}+\sum_{j=1}^{k_c}\left(\mathbf{f}_{c,ij}+\mathbf{f}_{d,ij}\right)+m_i\mathbf{g} \tag{1}$$

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

$$m_i c_{p,i}\frac{dT_i}{dt}=\sum_{j=1}^{k_i}Q_{i,j}+Q_{i,f}+Q_{i,rad}+Q_{i,wall} \tag{3}$$

where $\mathbf{v}_i$ and $\boldsymbol{\omega}_i$ are the translational and angular velocities of the particle, respectively, and k_c is the number of particles in interaction with the particle. The forces involved are: particle–fluid interaction force $\mathbf{f}_{pf,i}$, the gravitational force $m_i\mathbf{g}$, and inter-particle forces which include elastic force $\mathbf{f}_{c,ij}$ and viscous damping force $\mathbf{f}_{d,ij}$. The torques acting on particle i by particle j include: $\mathbf{M}_{t,ij}$ generated by tangential force, $\mathbf{M}_{r,ij}$ commonly known as the rolling friction torque. The equations to determine the particle–particle interactions forces and torques have been well documented, and widely used in the literature, as reviewed by Zhu et al. [24]. In this work, the simplified nonlinear force model based on the Hertz–Mindlin and Deresiewicz model is adopted due to its simplicity and intuitiveness. In this force model, a direct force–displacement relation for the tangential force, and the Hertz theory for the normal force and Coulumb friction force are used. For convenience, the force models used are listed in Table 1.

In the energy governing equation, $Q_{f,i}$ is the heat flux between fluid and particle i which locates in a computational cell, and $Q_{f,\,wall}$ is the fluid–wall heat flux. $Q_{i,j}$ is the heat flux between particles i and j due to conduction, $Q_{i,f}$ the heat flux by convection between particle i and its local surrounding fluid, $Q_{i,rad}$ the heat flux between particle i and its surrounding environment by radiation, $Q_{i,wall}$ particle–wall heat flux. The equations to calculate the different heat fluxes above are listed in Table 2. They are briefly discussed below.

The convective heat transfer rate between particle i and fluid is calculated according to $Q_{i,f}=h_{i,conv}\cdot A_i\cdot(T_{f,i}-T_i)$, where A_i is the particle surface area, $T_{f,i}$ is fluid temperature in a computational cell where particle i is located, and $h_{i,conv}$ is the convective heat transfer coefficient. $h_{i,conv}$ is associated with the Nusselt number, which is given by equation (a) in Table 2. Note that Pr is assumed to be constant in this work, set to 0.712 corresponding to that for air at 300 K. $a=1.2$ and $b=0.5$ are adopted as used in the reference [14]. Fluid–wall convective heat transfer rate is given by equation (b) in Table 2.

Conduction between particles mainly includes (i) particle–fluid–particle conduction heat transfer; and (ii) particle–particle conduction heat transfer. For particle–fluid–particle conduction heat transfer, Cheng et al. [25] formulated an equation to determine the heat flux, given by equation (c) in Table 2. For particle–particle conduction heat transfer, it includes two mechanisms: heat transfer through the static contact area between particles i and j, and heat transfer due to collision. Both heat flux can be respectively calculated by equation (d) and (e) in Table 2. Note that c' is the coefficient determined by a set of correlations, and the expressions can be found in the reference [14,26].

For the radiative heat transfer, an isolated domain for each particle is chosen to be its environment. In this specified enclosed cell, an environmental temperature is assumed to represent the enclosed surface temperature around such particle. Zhou et al. [14] calculated the heat flux due to radiation using the local environmental temperature to replace the bed temperature, and the equation is given by equation (e) in Table 2. Note that ε_{pi} is the sphere emissivity, assumed to be 0.8 in this work. The parameter $T_{local,i}$ is the averaged temperature of particles and fluid.

2.2. Fluid phase governing equations

The motion of the continuum fluid is calculated from the Navier–Stokes and continuity equations based on local mean variables over a computational cell, which can be written as:

$$\frac{\partial\varepsilon_f}{\partial t}+\nabla\cdot\left(\varepsilon_f\mathbf{u}\right)=0 \tag{4}$$