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Modelling fuel combustion in iron ore sintering

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ABSTRACT

In an iron ore sintering bed, the combustion behaviour of coke particles together with velocity of the flowing gas stream determines the temperature, width and speed of the traversing flame front. A bed heat treatment mathematical model was formulated in an earlier study to describe this complex relationship. An area of improvement in the model is the description of the coke combustion process, which is highly dependent on the resistances controlling the flow of gases to and from the coke particles. These vary for different coke particles because of the prior coarsening of the sinter mix by granulation. The characteristic structure of granules – nuclear particle with an adhering fines layer – indicates that gases have better access to finer coke particles. In this study, an available granulation model is integrated into the heat treatment model to provide a novel description of coke positioning within granules. In addition to this change, two endothermic reactions were introduced into the model. Using the previous and modified models, predicted bed temperature–time profiles as a function of position down the bed, were compared against embedded thermocouples results from seventeen laboratory sinter tests. Generally, the modified definition of coke combustion behaviour resulted in improved comparison with experimental results. In the sintering literature, studies have been reported on: the use of charcoal/biomass char to replace coke, the preferential placement of coke particles on the outside of granules, and varying the size distribution of the coke particles. Improving the access of gases to coke particles and decreasing coke size are comparable to using more reactive fuels. Combustion rate, efficiency and flame front properties are all influenced by fuel reactivity. Model predictions of changes in bed temperatures, flame front properties and sintering performance caused by fuel type, location and size are consistent with reported observations.

1. Introduction

Iron ore sintering is used all over the world to prepare agglomerates for the ironmaking blast furnace [1,2]. Figure 1 shows a schematic diagram of the major processes in a typical iron ore sintering plant. The blended sinter mix – typically composed of iron ores, fluxes, returned sinter fines, plant dust and about 4 wt.% coke breeze – is first granulated to coarsen its size distribution. Typically, the particles in a sinter mix would have sizes ranging from 0.0 to 9.0 mm. As water is added to the cascading mix in the granulating drum, the fines (typically smaller than 0.25 mm) adhere onto the surfaces of the coarser particles (typically greater than 1 mm). The granulated sinter mix is then charged onto the moving strand (in the region of around 3 m/min) via a roll feeder to form a bed of up to 0.8 m in height. As the bed travels under an ignition hood, coke particles on the upper surface are set alight to generate a narrow flame front. Air is continuously drawn through the bed by large fans and this causes the flame front to descend down the bed. The speed of the strand is adjusted so that the flame front reaches near the bottom of the bed close to its discharge. Sinter particles, suitable for blast furnace use, are released when the sintered block disintegrates on crushing.

In sintering, coke combustion supplies around 80% of the heat required to generate sufficient melt to form a strong sinter. As coke accounts for only around 4 wt.% of the total sinter mix, it is not surprising that small changes in its properties (e.g., size and ash value) can have a large effect on combustion behaviour, heat generation and sintering performance. Figure 2 summarises the upstream processes that influence coke combustion behaviour. The same figure also shows the downstream effect of coke combustion on the sintering process. The granulation process, in addition to influencing

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Nomenclature

$A_{ad,i}$	volumetric surface area of adhering coke particle of size i (m^2/m^3)
$A_{nu,i}$	volumetric surface area of nuclear coke particle of size i (m^2/m^3)
C	oxygen mole concentration (mol/m^3)
C_0	oxygen mole concentration at coke surface (mol/m^3)
C_1	oxygen mole concentration at coke core surface (mol/m^3)
C_2	oxygen mole concentration at granule surface (mol/m^3)
C_{O_2}	oxygen mole concentration in bulk gas (mol/m^3)
Cp_s	specific heat of solid (J/kg K)
D_1	effective oxygen diffusivity in ash layer (m^2/s)
D_2	effective oxygen diffusivity in adhering layer (m^2/s)
D_{O_2}	oxygen diffusivity in air (m^2/s)
F_i	fractional conversion of fixed carbon for coke size i (–)
$F_{ash,0}$	initial mass fraction of ash in coke (–)
F_v	gas flow resistance (Pa/m)
N_{size}	total number of size fractions (–)
N_g	total number of gas species (–)
N_s	total number of solid species (–)
N_r	total number of reactions (–)
P	gas pressure (Pa)
$R_{ad,i}$	reaction rate of adhering coke of size i (kg/m^3 s)
$R_{nu,i}$	reaction rate of nuclear coke of size i (kg/m^3 s)
R_u	universal gas constant (J/mol K)
T_g	gas temperature (K)
T_s	solid temperature (K)
W_c	carbon molecular weight (kg/mol)
W_i	molecular weight of gas species i (kg/mol)
$X_{0.5}$	granulation effectiveness (mm)
Y_i	mass fraction of gas species i (–)
d_0	initial diameter of coke particle (r_0 is its radius) (m)
d_1	diameter of coke core (r_1 is its radius) (m)
d_2	diameter of granule (r_2 is its radius) (m)
d_p	granule Sauter mean diameter (m)
h_{conv}	convection heat transfer coefficient (W/m^2 K)
h_g	specific enthalpy of gas (J/kg)
h_s	specific enthalpy of solid (J/kg)
$h_{m,ad,i}$	mass transfer coefficient of adhering coke particle of size i (m/s)
$h_{m,nu,i}$	mass transfer coefficient of nuclear coke particle of size i (m/s)
k_{al}	adhering layer mass transfer coefficient (m/s)
k_{ash}	ash layer mass transfer coefficient (m/s)
k_c	coke oxidation reaction rate constant (m/s)
k_{gbl}	gas boundary layer mass transfer coefficient (m/s)
k_r	chemical reaction rate constant (m/s)
$k_{s,eff}$	effective thermal conductivity of solid (W/m K)
m_c	instantaneous mass of fixed carbon (kg)
m_{c0}	initial mass of fixed carbon (kg)
$\dot{w}'''_{i,k}$	mass production rate of gas species i in reaction k (kg/m^3 s)
$\dot{w}'''_{j,k}$	mass production rate of solid species j in reaction k (kg/m^3 s)
$\dot{q}'''_{g,k}$	volumetric heat source of gas phase in reaction k (J/m^3 s)
$\dot{q}'''_{s,k}$	volumetric heat source of solid phase in reaction k (J/m^3 s)
r	particle radial position (m)
t	time (s)
u_g	gas velocity (m/s)
y	distance down bed (m)

Greek symbols

Φ_s	particle sphericity (–)
α_i	partition coefficient for particle size i (–)
δ_i	adhering layer thickness for particle size i (mm)
ε	bed voidage (–)
ε_{al}	porosity of adhering layer (–)
ε_{ash}	porosity of ash layer (–)
$\varepsilon_{coke,0}$	porosity of initial coke particle (–)
η	combustion efficiency (–)
μ_g	dynamic viscosity of gas (kg/m s)
θ	ratio of layer mass to total mass (–)
ρ_b	bulk density of bed (kg/m^3)
ρ_g	true density of gas (kg/m^3)
τ_{al}	tortuosity factor of adhering layer (–)
τ_{ash}	tortuosity factor of ash layer (–)

coke location and access to oxygen during combustion, will determine the structural properties of the bed formed for sintering. At a fixed suction, properties such as bed porosity and height will determine airflow rate through the bed and, consequently, the coke combustion process and flame front speed. If sufficient fan capacity is available, airflow rate can be increased through increasing suction. For a fixed airflow rate, bulk density changes – for example through increasing the level of porous ore and granule size – will influence heat transfer down the bed and flame front speed.

On the downstream side (right side of Fig. 2), producing a sinter of suitable quality at the lowest fuel rate and the highest productivity is the ultimate goal of most operations. The properties of the flame front have a major effect on these three plant performance indicators. The three critical flame front properties are flame front temperature (FFT), flame front width (FFW) and flame front speed (FFS) – the latter two determining the (flame front or heating) residence time as the front traverses a local region in the bed. The properties of the flame front are strongly dependent on the combustion behaviour of coke particles in the bed.

Mathematical models are available to describe many of the processes in Fig. 2, for example: granulation, bed permeability before and during sintering, and bed temperatures as the flame front traverses [3,4]. Clearly, an important factor in predicting heat transferred to the bed from the flame front is the combustion efficiency of the coke combustion process. To better define the combustion behaviour of coke particles, the effect of granulation has to be taken into account because of its influence on coke particle location.

The combustion and gasification of coke/char has been extensively considered in fixed beds (e.g., [5,6]), moving beds (e.g., [7]), pulverized coal combustors (e.g., [8,9]) and circulating fluidized beds (e.g., [10]). In contrast, only a limited number of coke combustion models for iron ore sintering have been reported since the 1970s [11–15]. A simple rate-controlling model which takes into account the resistance of the gas film diffusion and reaction at the interface is most widely adopted [13,15]. Yang et al. [16] introduced another resistance – that of diffusion through the ash layer. Toda et al. [17] considered that with the generation of melt, coke combustion rate reduces because the diffusion efficiency of oxygen to coke particles declines. To reflect changing gas concentration within a granule, Cumming et al. [11] proposed the inclusion of an empirical availability factor into the model. To describe the coke combustion process, Zhou et al. [4] combined the resistance of the adhering fines layer with the diffusion