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Modelling and analysis of the combustion behaviour of granulated fuel particles in iron ore sintering

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The combustion behaviour of solid fuels – for example, coke and biomass char – is an important consideration in iron ore sintering as it determines heat availability for the melt formation process. This behaviour is influenced by the presence of an adhering layer of fine material around the fuel particles. In this study, analytical results for the combustion of single granulated fuel particles – applicable to all Thiele modulus (ϕ_h) values – are presented. For the conversion of an isothermal carbon particle, the conversion parameter α is found to depend on ϕ_h and the effectiveness factor η_h. For $\phi_h < 9$, α can be approximated by $0.4\eta_h$, while for $\phi_h > 9$, α approaches $\eta_h/3$. The relationship between α and η_h is not altered by the presence of an adhering layer. However, at high temperatures and for reactive fuels, an adhering layer influences the combustion rate significantly. The fuel combustion process in iron ore sintering can be viewed as occurring in three regimes depending on factors such as fuel size, reactivity and temperature. To investigate the effect of fuel properties on sintering performance, the developed combustion model is integrated into a 2D iron ore sintering model. Good comparisons are obtained between model results and experimental data from laboratory sintering tests. In the study of fuel types, model results indicate that when biomass char replaced coke there was significant lowering of flame front temperature and combustion efficiency, while the speed of the flame front down the bed accelerated. These changes can be explained by the higher reactivity of the biomass char and its physical properties which influence the granulation process – resulting in changes in the thickness of the adhering layer and combustion behaviour. The flow-on effect of this on sintering performance is consistent with reported experimental results by other researchers.

1. Introduction

Sintering is very widely used around the world to prepare a lumpy ferrous feed for the ironmaking blast furnace. The sintering process involves the formation of a bed on a strand and the sequential combustion of solid fuel particles (typically coke) in the bed to form a narrow flame front, which travels downwards. In recent years, the combustion behaviour of solid fuel particles in iron ore sintering has attracted much attention [1–6]. This is partly because there is around 4 wt% of coke breeze (typically smaller than 3 mm) in a sinter mix providing approximately 80% of the total heat required to produce competent furnace sinter. In a previous publication, a one-dimensional (1D) sinter model was developed and used to provide fundamental understanding of the coke particle combustion behaviour [1]. It is noted that the combustion of coke particles can be simulated using shrinking-core models developed in the literature [1,4,7–12], and most of the sintering models have made the inherent assumption that combustion behaviour in sintering is similar to that found in pulverized coal or fluidized bed combustors. However, this is not strictly the case because most coke particles are surrounded or encapsulated by fine material. This happens because the sinter mix is coarsened in a granulating drum prior to discharging onto the strand. Very simply, the process involves the addition of water to the mix as it cascades in the drum and most coke particles are integrated into granules or encapsulated by a thin layer of fines. Previous results indicate that when the effects of the fines layer (around the particles) and the ash layer (which increases as combustion progresses) are

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Nomenclature

C oxygen mole concentration ($kmol/m^3$)
C_0 oxygen concentration at r_{c0} at first combustion stage (dimensionless)
C_∞ oxygen mole concentration in bulk gas ($kmol/m^3$)
Cs instantaneous carbon mole concentration in coke ($kmol/m^3$)
Cs_0 initial carbon mole concentration in coke ($kmol/m^3$)
D_{e1} effective oxygen diffusion coefficient in reacting coke core (m^2/s)
D_{e2} effective oxygen diffusion coefficient in coke ash layer (m^2/s)
D_{e3} effective oxygen diffusion coefficient in adhering layer (m^2/s)
D_k Knudsen diffusion coefficient of oxygen in coke core (m^2/s)
D_{O2} oxygen diffusion coefficient in bulk gas (m^2/s)
F_{ash0} initial mass fraction of ash in coke (dimensionless)
$N_{ad,i}$ number density of adhering coke particles of size interval i in packed bed ($1/m^3$)
$N_{nu,i}$ number density of nuclear coke particles of size interval i in packed bed ($1/m^3$)
N_{size} total number of coke size intervals (dimensionless)
$R_{ad,i}$ reaction rate of adhering coke particles of size interval i (kmol/s)
$R_{nu,i}$ reaction rate of nuclear coke particles of size interval i (kmol/s)
R_c reaction rate of (single) carbon particle (kmol/s)
$R_{c,all}$ reaction rate of all nuclear and adhering coke particles for full size distribution per unit bed volume ($kmol/m^3$ s)
R_u universal gas constant (J/mol K)
Sh_3 equivalent Sherwood number (dimensionless)
Sm_{c0} specific surface area of coke core (m^2/kg)
T_{air} ambient air temperature around external pot wall (K)
T_g gas temperature (K)
T_s solid temperature (K)
V_c volume of carbon particle (m^3)
W_c carbon molecular weight (kg/kmol)
W_{O2} oxygen molecular weight (kg/kmol)
X conversion ratio of carbon (dimensionless)
h_{air} convection transfer coefficient at external pot wall (W/m^2 K)
h_m mass transfer coefficient (m/s)
$h_{g\text{-}w}$ gas-to-wall heat transfer coefficients at inner pot wall (W/m^2 K)
$h_{s\text{-}w}$ solid-to-wall heat transfer coefficients at inner pot wall (W/m^2 K)
k_{al} adhering layer mass transfer coefficient (m/s)
k_{ash} ash layer mass transfer coefficient (m/s)
k_{pr} mass transfer coefficient considering the combined effects of pore diffusion and surface reaction (m/s)
k_{gbl} gas boundary layer mass transfer coefficient (m/s)
k_v reaction rate constant based on volume (m^3/kmol s)
m_c instantaneous carbon mass (kg)
m_{c0} initial carbon mass (kg)
$q_{g\text{-}w}$ gas-to-wall heat flux at pot wall (W/m^2)
$q_{s\text{-}w}$ solid-to-wall heat flux at pot wall (W/m^2)
r particle radius coordinate (m)
r_3 radius of granule (including adhering layer) (m)
r_c instantaneous carbon radius (m)
r_{c0} initial carbon radius (m)
r_{pore} average radius of pores in coke core (m)
t time in coke combustion modelling system (s)
t' time in CFD modelling system (s)
$x_{0.5}$ particle size giving a partition coefficient of 0.5 (m)

Greek symbols
$\Delta t'$ length of time step in CFD modelling system (s)
α conversion mode parameter in Eq. (1) (dimensionless)
β conversion mode parameter in Eq. (2) (dimensionless)
χ_i partition coefficient of particle size interval i (dimensionless)
δ_i adhering layer thickness of coke particle size interval i (m)
ε_{al} porosity of adhering layer (dimensionless)
ε_{ash} porosity of ash layer (dimensionless)
ε_{c0} porosity of initial coke core (dimensionless)
ϕ_0 Thiele modulus based on initial coke radius r_{c0} (dimensionless)
ϕ_h Thiele modulus based on instantaneous coke radius r_c (dimensionless)
η effectiveness factor defined in Eq. (26) (dimensionless)
η_1 effectiveness factor for the first combustion stage (dimensionless)
η_2 effectiveness factor for the second combustion stage (dimensionless)
η_h effectiveness factor defined in Eq. (83) (dimensionless)
φ dimensionless oxygen concentration (C/C_∞) (dimensionless)
φ_0 dimensionless oxygen concentration at r_{c0} at first combustion stage (dimensionless)
φ_c dimensionless oxygen concentration at r_c at second combustion stage (dimensionless)
φ_2 dimensionless oxygen concentration at r_{c0} at second combustion stage (dimensionless)
φ_3 dimensionless oxygen concentration at r_3 (dimensionless)
λ_W thermal conductivity of pot wall (W/m K)
ν stoichiometric coefficient for carbon and oxygen reaction (dimensionless)
ρ_c instantaneous carbon apparent density (kg/m^3)
ρ_{c0} initial carbon apparent density (kg/m^3)
σ a measure of the spread of the intermediate size ranges (dimensionless)
ω_{al} tortuosity factor of adhering layer (dimensionless)
ω_{ash} tortuosity factor of ash layer (dimensionless)
ω_{c0} tortuosity factor of initial coke core (dimensionless)
ξ dimensionless radius (r/r_{c0}) (dimensionless)
ξ_3 dimensionless radius of granule (r_3/r_{c0}) (dimensionless)
ξ_c instantaneous dimensionless carbon radius at second combustion stage (r_c/r_{c0}) (dimensionless)
ψ dimensionless carbon concentration (Cs/Cs_0) (dimensionless)
ψ_{cr} dimensionless carbon concentration at the end of the first stage (dimensionless)
τ dimensionless time (dimensionless)
τ_{cr} dimensionless time at the end of first combustion stage (dimensionless)