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Analysis of char–slag interaction and near-wall particle segregation in entrained-flow gasification of coal

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ABSTRACT

The fate of carbon particles during entrained-flow gasification of coal in the slagging regime is analyzed. More specifically, the study addresses the relevance of segregation of carbon particles in a near-wall region of the gasifier to coal conversion. Segregation of carbon particles is analyzed considering the effects of turbulence- and swirl-promoted particle migration toward the wall, interaction of the impinging particles with the wall ash layer, coverage of the slag layer by refractory carbon particles, accumulation of carbon particles in a dense-dispersed phase near the wall of the gasifier. Operating conditions of the gasifier and slag properties may be combined so as to give rise to a variety of conversion regimes characterized by distinctively different patterns of carbon particles segregation.

A simple 1D model of an entrained-flow gasifier has been developed based on the conceptual framework of carbon particle segregation. The model aims at providing a general assessment of the impact of the different patterns of carbon particle segregation on the course and extent of carbon gasification. A sensitivity analysis with reference to selected model parameters is performed to identify key processes controlling carbon segregation and their impact on the gasifier performance.

1. Introduction

Entrained-flow coal gasifiers of new generation are characterized by high peak operating temperatures, aiming at promoting ash melting, and by multi-stage feedings of coal and gaseous reactants. Flow fields inside the oxidizer/reducer chambers are carefully optimized so as to favor ash migration/deposition onto the reactor walls, whence flow and collection of the slag at the bottom of the gasifier eventually take place. Despite the fact that several entrained-flow gasifiers have been in operation for decades, modeling coal gasification under entrained-flow conditions is still a challenging goal with broad areas of uncertainty. Early one-dimensional models, developed in the late seventies/eighties [1,2], were based on the assumption that the gas and solid phases both moved in plug flow. More comprehensive models, supported by CFD-based detailed descriptions of flow, temperature and concentration fields, considered the relevance of complex hydrodynamics and multiphase flow to the gasifier's performance [3–7]. The dynamics of ash particles in the gasification chamber have been the subject of several studies focused on the build-up of the wall slag layer. The flow patterns before deposition and the thermal/rheological behavior of the slag have also been assessed [8–12]. Criteria for ash particle deposition upon impact on the wall layer of molten slag have been developed by relating the effectiveness of particle–slag incorporation to viscosities of the colliding particle and of the slag target, on one hand, to the probability of collisions between unfused particles, on the other [13–19]. A detailed analysis of the dynamics of char particles as they impinge on the slag layer has been recently developed by taking into account the interplay of inertial, viscous and interfacial forces acting on a particle [20]. Most analyses of char–slag interaction, however, are focused on the issues of slag build-up and flow, whereas the fate of unconverted carbon associated with char particles transferred to the molten ash slag has received comparatively limited attention [5,19,21,22]. Tominaga et al. [5] already recognized the relevance of char migration and deposition onto the wall slag layer as one pathway to carbon burn-out. Wang et al. [22] modeled slagging combustion of carbon taking into account the extensive contribution to carbon burn-out due to char deposition on the slag layer and combustion of char particles attached to the slag. The influence of the 'wall burning' phenomenon on levels of unconverted carbon as well as on the thermal effects associated with the course of heterogeneous chemical reactions were quantitatively assessed by model computations.

This paper addresses the fate of coal particles during entrained-flow gasification in the slagging regime. More specifically, the relative importance of the parallel pathways of coal conversion consisting of entrained-flow of carbon particles in a lean-dispersed gas phase versus segregated flow of the particles in a near-wall

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Nomenclature

C	concentration of solids (kg m^{-3}) or of gaseous species (kmol m^{-3})
D	gasifier internal diameter (m)
d	particle diameter (m)
F	mass flow rate of solids (kg s^{-1}) or molar flow rate of gaseous species (kmol s^{-1})
K	equilibrium thermodynamic constant (–)
k_0	parameter appearing in the expression for $k_m(z)$ (Eq. (32)) (m^{-1} s^{-1})
k_{kin}	lumped kinetic constant of C gasification (s^{-1})
k_{m}	bulk-to-wall mass-transfer coefficient (s^{-1})
L	length of the gasifier (m)
$\dot{m}$	bulk-to-wall flux (kg m^{-2} s^{-1})
P	pressure (bar)
Q	gas volumetric flow rate (m^3 s^{-1})
$\Re$	ideal gas constant (bar m^3 kmol^{-1} K^{-1})
r	rate of reaction (kg m^{-3} s^{-1})
S	gasifier cross-sectional area (m^2)
T	temperature (K)
u	impact velocity (m s^{-1})
v	velocity (m s^{-1})
x	progress variable of the water–gas shift reaction (Eq. (12)) (kmol m^{-3})
X_C	overall carbon conversion degree (–)
z	axial coordinate of the gasifier (m)
z^*	parameter appearing in the expression for $k_m(z)$ (Eq. (32)) (m)
α	parameter appearing in the kinetic expressions (Eqs. (27) and (28)) (–)
β	parameter appearing in the balance equations on gaseous compounds (Eq. (15)) (–)
γ	parameter appearing in the kinetic expressions (Eqs. (27) and (28)) (–)
δ	slag thickness (m)
$\dot{\delta}$	rate of change of the slag thickness (m s^{-1})
μ	slag viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
σ	interfacial particle–slag tension (kg s^{-2})

Subscripts

ash, char, chemical formulae	relative to the pertinent species
C	relative to carbon in char/soot
dry	relative to the dry carbon gasification (Eq. (11))
steam	relative to the steam carbon gasification (Eq. (10))

Superscripts

dense	relative to the dense-dispersed phase
in	relative to the stage I inlet
lean	relative to the lean-dispersed phase
lim	limiting value
slag	relative to the slag phase

region of the gasifier promoted by particle migration and interaction with the molten slag is assessed. A simple 1D model has been developed starting from a conceptual analysis of the micromechanics of particle–slag interaction and char segregation. Computations are directed to the assessment of the prevailing pathway to coal gasification as a function of the operating conditions.

2. Conceptual analysis of the micromechanics of particle–slag interaction

A conceptual analysis of the fate of coal particles during entrained-flow gasification is hereby developed. Coal particles, injected into the gasification chamber, contribute to the formation of a lean-dispersed particle-laden gas flow. Particle migration from the lean-dispersed phase toward the chamber walls, where build-up of a molten ash layer takes place, is induced by a combination of mechanisms:

(i) *Inertial mechanism*, associated with centrifugal forces due to swirl or tangential flow, relevant to coarser particles.
(ii) *Turbulence-promoted dispersive mechanism*, associated with 'turbophoretic' transport due to turbulent gas flow fields in the vicinity of confining walls, relevant to finer particles.

The fate of char particles as they interact with the wall slag layer must take into account the composite nature of the char, consisting of ash, typically fusible at the gasification temperatures, and residual carbon, inherently refractory and unfusible. Li and Whitty [23] investigated the char–slag transition during entrained-flow oxidation of coal particles. They observed that a distinct transition from porous, non-sticky char to molten, sticky slag occurred at temperatures above the ash flow temperature only when carbon conversion exceeded 90%. Based on Li and Whitty's findings, it can be assumed that char particles interact with the wall layer like unfused particles unless they are in the very late burn-off stage.

The possible interactive patterns associated with impingement of a char particle on the wall slag layer's surface depend on the combined effect of: (a) particle inertia; (b) ash-carbon interfacial tension, which drives carbon segregation at the slag surface; (c) ash viscosity; (d) buoyancy, active only in non-vertical orientation of the gasifier's walls.

2.1. Criterion for char particle entrapment inside the wall ash layer

Permanent entrapment of the char into the slag layer may occur if impinging char particles plunge well within the slag layer. Plunging requires particle inertia to overcome viscous and interfacial forces, which both counteract penetration of the impinging particle into the wall slag layer. Shannon et al. [20] have recently developed a detailed analysis of the dynamics of a carbon particle after impact on the wall slag layer. A simplified criterion for particle plunging is hereby developed based on an order-of-magnitude assessment of the energetics of particle–slag interaction. The kinetic energy associated with the normal component of the impact velocity of the char particle against the slag u is given by:

$$\frac{1}{2}\frac{\rho_{\text{char}}\pi d^3}{6}u^2 \tag{1}$$

This must be compared with the work terms associated with the viscous Stokes' force and with the interfacial particle–slag tension as the particle plunges into the molten ash. For complete particle entrapment, the cumulative work of interfacial and viscous forces is approximately given by:

$$3\pi\mu u d^2 + \sigma\pi d^2 \tag{2}$$

Accordingly, the criterion for particle plunging requires the particle kinetic energy at the impact to exceed the cumulative work of viscous and interfacial forces:

$$\frac{\rho_{\text{char}} d u^2}{12} > 3\mu u + \sigma \tag{3}$$