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A lab-scale cold flow model reactor to investigate near-wall particle segregation relevant to entrained-flow slagging coal gasifiers

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HIGHLIGHTS

- Understanding of particle–wall interactions in entrained gasifiers is pursued.
- The real system was downscaled into a lab-scale cold entrained-flow reactor.
- Molten wax was air-atomized into a mainstream of air.
- Insights into the interaction particles/wall liquid layer were provided.
- The fractional mass of dispersed phase ranged from 91% to 12% along the reactor.

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ABSTRACT

This paper reports on preliminary results of an experimental investigation aimed at the development of a phenomenological model of the fate of coal/ash particles in entrained-flow slagging coal gasifiers. The study specifically addresses the interaction between the lean-dispersed particle phase and the reactor walls, and the establishment of a particle segregated phase in the near-wall region of the gasifier. Better mechanistic understanding of particle–wall interaction patterns in entrained-flow gasifiers is pursued using the tool of physical modeling. To this end a lab-scale cold flow reactor (0.04 m-ID) has been designed and set up, where molten wax is air-atomized (droplets of 50–100 μm size) into a mainstream of air to simulate the near-wall fate of char/ash particles in a real hot environment. Preliminary characterization of the hydrodynamics of the lean-dispersed phase, of its interaction with the wall, of the build-up of the liquid wall layer has been accomplished with a focus on the "sticky wall–sticky particle" sub-regime.

The particle deposition rate at the wall and the partitioning of wax droplets between the lean-dispersed phase and the wall liquid layer have been assessed under a range of operating conditions. Temperatures of the atomized wax, of the mainstream air and of the reactor wall have been set in a range of values (120–155 °C) at which the wax was fluid. Experiments with wax feeding rate of 0.2 g s^{-1} and flow rate of atomizing air in the order of 0.30 m^3 h^{-1} demonstrated that the fractional mass of wax in the dispersed phase decreased from 91% to 12% as the reactor length increased from 0.03 m to 0.27 m. The velocity of the descending wall liquid layer, whose thickness was in the order of 0.2 mm, ranged between 3 mm s^{-1} and 6 mm s^{-1}. The effects of the flow rate of atomization air and of the nozzle temperature were limited.

1. Introduction

Modern entrained-flow coal gasifiers are characterized by operating conditions that promote ash migration/deposition onto the reactor walls, whence the molten ash is drained and quenched at the bottom of the gasifier as a vitrified slag [1–7]. The recent literature on entrained-flow gasification has addressed the fate of char particles as they impinge on the wall slag layer [8–15]. This research group has recently contributed to develop a phenomenological model of the fate of coal/ash particles, which considers the establishment of a particle segregated phase in the near-wall region of the gasifier [16]. More specifically, it has been highlighted that char particles impinging on the wall slag layer can: (i) be entrapped inside the melt, and this prevents further progress of combustion/gasification (*entrapment* regime, Fig. 1); (ii) adhere onto the slag layer's surface without being fully engulfed, and this permits further progress of combustion/gasification (*segregation*

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Nomenclature

D	reactor inner diameter (m)
L	reactor length (m)
Q	gas volumetric flow rate ($m^3\ s^{-1}$)
q	axial wax mass flux ($kg\ m^{-2}\ s^{-1}$)
R	reactor inner radius (m)
r	radial coordinate (m)
T	temperature (°C)
W	wax mass flow rate ($kg\ s^{-1}$)
X_C	carbon conversion degree (–)
y	fractional mass of wax (–)
z	axial distance from the nozzle (m)

Greek symbols

θ	spray angle (°)

Subscripts

a	atomization
max	maximum value
ms	mainstream
w	wall
wax	wax

Superscripts

*	geometrical condition of droplet impingement
lean	lean (dispersed) phase
th	threshold value

regime, Fig. 1). In the latter case, and if the coverage of the slag layer with carbon particles is extensive, a dense-dispersed annular phase may establish in the close proximity of the wall ash layer, where the excess impinging char particles that cannot be accommodated on the slag surface accumulate (*segregation–coverage* regime, Fig. 1). This annular phase is likely to be characterized by a velocity that is intermediate between that of the fast lean-dispersed particle phase and that of the slowly moving molten ash wall layer (Fig. 1). This feature is beneficial to C conversion, as it gives rise to a longer mean residence time of carbon particles belonging to this dense phase (with respect to what happens in the lean phase). This phenomenological model has received qualitative validation from analysis of the properties of ash streams generated in a full-scale entrained-flow gasification plant [17]. Moreover, the complex phenomenology associated with the interaction of a particle-laden turbulent flow with the inelastic slag-covered wall of the gasifier has been the subject of numerical simulation [18,19]. These studies confirmed that near-wall accumulation of particles may be extensive and that particle segregation is relevant to the performance of slagging entrained-flow gasifiers, as it affects the course of heterogeneous combustion/gasification reactions and the properties of the syngas.

The present study aims at improving the mechanistic understanding of particle–wall interactions and segregation patterns in entrained-flow gasifiers. The tool is that of physical modeling. Phenomenological and quantitative features of particle–wall interaction have been investigated in a lab-scale cold entrained-flow reactor equipped with a nozzle whence molten wax is air-atomized into a mainstream of air. The temperature of the mainstream is adjusted so as to tune the solid vs liquid state and the viscosity (and "stickiness") of the wax droplets. The temperature of the wall may also be adjusted to control the formation, viscosity and stickiness of the liquid wall layer. Assessment of the flow and segregation patterns in the reactor is based on direct visual observation, as the reactor is optically accessible. Moreover, the partitioning of the wax droplets/particles into a dilute-dispersed phase, a dense-dispersed phase and the layered liquid material flowing on the wall is characterized by selective collection of the different phases at the exhaust of the reactor. The model reactor and the test protocol aim at providing insight into the detailed mechanisms of interaction between dispersed particles, in the molten, plastic or solid state, and the wall liquid layer.

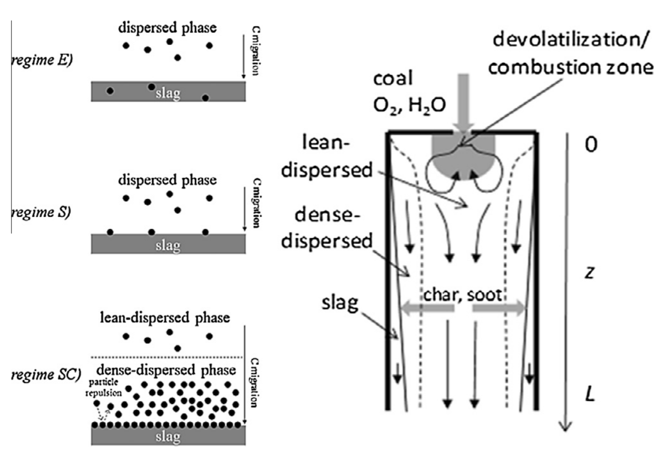

Fig. 1. Left: near-wall segregation regimes (E = *entrapment*; S = *segregation*; and SC = *segregation-coverage*). Right: schematic diagram of the entrained-flow gasifier.

2. Micromechanics of particle–slag interaction

Coal particles are fed to the gasification chamber through nozzles as a lean-dispersed particle-laden gas flow. Particle transport to the wall is controlled by inertial forces, possibly enhanced by swirled or tangential flow, and by the "turbophoretic" component related to the interaction between turbulent flow structures and the reactor walls (turbulence-promoted dispersive transport) [16]. In particular, inertia is relevant to coarser particles, turbophoresis to finer ones. Both mechanisms play a significant role in transport of particles from the dispersed phase to the walls and in the build-up of a slag layer [16].

A further key to the establishment of regimes outlined in Fig. 1 is represented by the stickiness of the particle and of the wall layer. Plastic behaviour and stickiness are emphasized as the content of the inherently refractory carbon decreases, i.e. as the carbon conversion degree X_C increases (Whitty and co-workers [9–11] set the threshold for plastic or viscous behaviour around X_C = 90% for chars derived from subbituminous and bituminous coals) and as the temperature is beyond the ash melting point. Yong et al. [14] described different particle–wall interaction patterns on the basis of the stickiness of the impinging particles and of the wall layer. These patterns are outlined in Fig. 2:

(i) *Sticky wall–sticky particle (SW–SP)*: char particles with low carbon content (large X_C) impinge on the slag layer (Fig. 2a).
(ii) *Sticky wall–non sticky particle (SW–NSP)*: particles characterized by large C content impinge on the slag layer (Fig. 2b).