NEAR-WALL PHENOMENA IN ENTRAINED-FLOW SLAGGING GASIFIERS

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Abstract
This paper deals with near-wall particle segregation phenomena in entrained-flow slagging coal gasifiers. The recent literature has addressed the fate of char particles by assessing the relative importance of coal conversion associated with the entrained-flow of carbon particles in a lean-dispersed phase and the segregated flow of char particles in a near-wall dense-dispersed phase. Different micromechanical char–slag interaction patterns may establish, depending on the stickiness of the wall layer and of the impinging char particle. The main objective of this study is to use the tool of the physical modelling, to give a contribution in the development of a phenomenological scenario of the fate of coal/ash particles in entrained-flow slagging coal gasifiers, which considers the establishment of a particle segregated phase in the near-wall region of the gasifier. Different scales of investigation were pursued, relevant to study the fluid dynamic conditions which lead to near-wall particle segregation, as well as the particle–wall micromechanical interactions. Montan wax was used to mimic, at atmospheric conditions, particle–wall interactions relevant in entrained-flow gasifiers. As a matter of fact, this wax had rheological/mechanical properties resembling those of a typical coal slag (under molten state) and those of char particles (under solid state).

1. Introduction

Understanding the phenomenology and proper design of slagging entrained-flow gasifiers requires the assessment of the fate of char particles as they impinge on the wall slag layer. The relative importance of coal conversion associated with the entrained-flow of carbon particles in a lean-dispersed phase and the segregated flow of char particles in a near-wall dense-dispersed phase has been recently studied [1–3]. In a previous study, Montagnaro and Salatino [4] developed a phenomenological model that considers the establishment of a particle segregated phase in the near-wall region of the gasifier. It was highlighted that char particles impinging on the wall slag layer can either be entrapped inside the melt (progress of combustion/gasification is hindered), or adhere onto the slag layer's surface (progress of combustion/gasification is still possible). In the latter case, and if the slag layer is extensively covered by char particles, a particle segregated 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. This annular phase is slower than the lean particle-laden gas phase, so that the segregated char particles residence times are longer than the average gas space-time, with a positive impact on carbon burn-off. Further studies confirmed the soundness of this phenomenological framework [5,6]. Particle–wall interaction occurs according to different micromechanical patterns, which depend on parameters such as particle and wall temperatures, solid/molten status of the particles and wall layer, char conversion degree, surface tension of the slag layer, particle effective stiffness and char/slag interfacial tension. Char–slag interaction patterns are hereby classified on the basis of the *stickiness degree* of the wall layer and of the char particle:

- the material laying on the wall (prevailingly, inorganic ash) is *sticky* when the wall temperature is high enough to ensure an ash molten status, generating a liquid slag layer. An additional condition for the slag layer to be sticky is that it must not be extensively covered by *non sticky* char particles;
- the char particle is sticky when its temperature is beyond the ash melting point, and its carbon conversion degree is beyond a given threshold value, as the plastic behaviour is emphasized when the carbon content is reduced.

On the basis of this classification, four interaction scenarios can be considered, namely: *(i)* non sticky char/ash particles impinging on a molten-slag-covered sticky wall (*NSP–SW*); *(ii)* non sticky char/ash particles impinging on a non sticky wall (*NSP–NSW*); *(iii)* molten, i.e. sticky, ash particles impinging on a non sticky wall (*SP–NSW*); *(iv)* molten sticky ash particles impinging on a sticky wall (*SP–SW*).
This study aims at investigating near-wall particle segregation by using a lab-scale cold entrained-flow reactor. The cold flow model reactor ensures the formation of a dispersed phase and a near-wall layer to reproduce and characterize the four micromechanical interaction patterns. Furthermore, micromechanical particle–wall interaction patterns were studied by means of an appropriate experimental rig which permitted to record a single particle impact on a flat surface.

2. Experimental

The investigation of near-wall segregation phenomena was carried out in a lab-scale optically accessible cold entrained-flow reactor (0.1 m-ID), where molten wax was air-atomized (droplets of 10–100 μm size) into an air mainstream to simulate the fate of char/ash particles in a real hot environment (Figure 1 (left)). The plastic/fluid behaviour of softened or molten ash and of the wall slag layer has been simulated, at nearly ambient conditions, by molten wax as a surrogate of fuel ash. Waradur E™ (Völpker Spezialprodukte, Germany) was selected, as the rheological/mechanical properties of this wax resembled those of a typical coal slag [6,7]. Moreover, mechanical properties of solid wax well agree with data for coal/char, confirming the suitability of this wax to mimic also the char behaviour [8]. Details on the experimental rig and operation are described elsewhere [7,8]. In order to correctly operate the lab-scale reactor in the four interaction regimes, three temperatures were tuned: the atomization temperature (T_a), i.e. the nozzle exit temperature, the mainstream air temperature T_{ms}, the wall temperature T_w. The other two operating parameters are Q_a and Q_{ms}, i.e. the flow rate of atomization and mainstream air, respectively. Results reported hereinafter refer to the following sets of operating parameters (Q_a and Q_{ms} refer to 273 K):

- *NSP–NSW*: T_a=100°C, T_{ms}=30°C, T_w=30°C, Q_a=0.5 m^3 h^{-1}, Q_{ms}=1 m^3 h^{-1};
- *NSP–SW*: T_a=100°C, T_{ms}=30°C, T_w=150°C, Q_a=0.5 m^3 h^{-1}, Q_{ms}=2 m^3 h^{-1};
- *SP–NSW*: T_a=120°C, T_{ms}=90°C, T_w=30°C, Q_a=0.275 m^3 h^{-1}, Q_{ms}=1 m^3 h^{-1};
- *SP–SW*: T_a=110°C, T_{ms}=160°C, T_w=140°C, Q_a=0.275 m^3 h^{-1}, Q_{ms}=1 m^3 h^{-1}.

Experimental tests aimed at characterizing the phenomenology of the interaction between the dispersed phase generated by the spray and the reactor walls. The reactor length was varied to study the influence of the distance *z* from the injection nozzle on the fractional mass of wax transferred form the lean-dispersed phase to the wall layer ($y^{wall}(z)$). To obtain y^{wall}, the apparatus was equipped with a system (see Figure 1 (left)) able to separately collect the material exiting the reactor in the lean and wall phases.

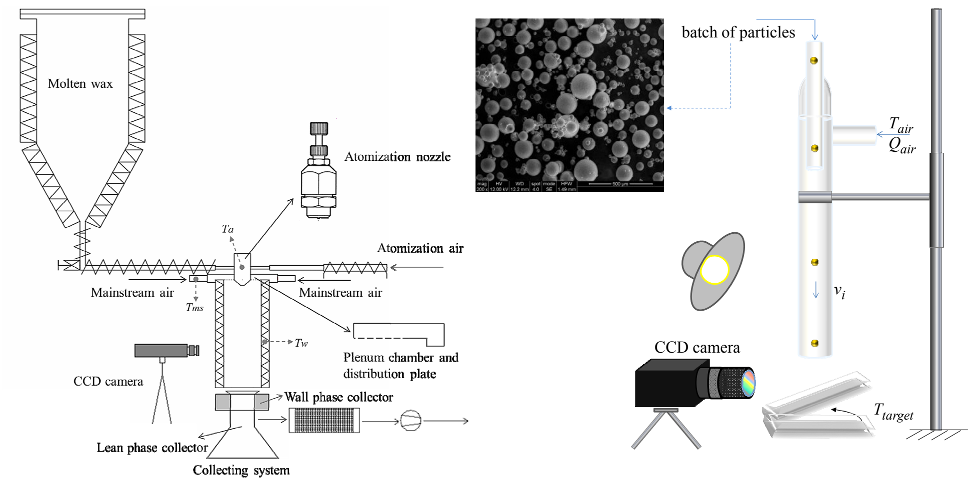

Figure 1. Scheme of the experimental rigs for the investigation of near-wall segregation phenomena (left) and of particle–wall micromechanics (right).

Moreover, an investigation of the micromechanical particle–wall interactions was pursued by means of another experimental rig (Figure 1 (right)), consisting of a vertical Pyrex tube, 0.65 m-height and 0.03 m-ID, connected at the top with another Pyrex tube (0.01 m-ID and 0.013 m-OD) running coaxially for 0.08 m inside the larger tube. Batches of wax particles (75±15 μm) were fed into the smaller tube by means of a Pasteur pipette. Air was fed sideways at the top of the tube, while the particles flowed through the inner tube driven by gravity, and then in the outer tube where they were entrained by the air flow. The particle impact velocity was controlled regulating the air flow rate. When the particles exited the tube, they impacted on a target plate placed around 0.05 m below the bottom end of the tube (impact angle=84±4°). The experimental tests aimed at characterizing the phenomenology of particle–wall interaction from a micromechanical point of view, in terms of restitution coefficient calculated by post-processing impact and rebound particle velocity data as assessed by the aid of a CCD camera. In particular, results for the normal restitution coefficient ε_n as a function of different values for the normal impact velocity v_{ni} in the *NSP–NSW* regime are shown. Results were obtained for five different target surfaces.

3. Results and Discussion

Figure 2 reports $y^{wall}(z)$ profiles for the four interaction regimes. Limiting curves corresponding to full segregation (i.e., instantaneous capture of impinging particles, ideal *SP–SW* regime [6]) and to no segregation ($y^{wall}=0\ \forall z$, namely ideal *NSP–NSW* regime) are reported for comparison. The axial coordinate $z^*\approx 0.13$ m corresponds to the intersection of the outer surface of the conical spray jet with the cylindrical reactor wall [6]. It represents the theoretical limit beyond which wax transfer from the lean to the wall phases should take place. Analysis of Figure 2 suggests that particle segregation takes place in any regime, to an extent that depends on the stickiness of the particles and of the wall. Experimental results are fairly consistent with the limiting full segregation theoretical curve for *SP–SW*, *SP–NSW* and *NSP–SW* regimes, i.e. whenever either the particle or the wall (or both) are sticky. Transfer of wax to the wall takes place beyond the limiting coordinate $z^*=0.13$ m at a rate that is consistent with the theoretical limiting curve. y^{wall} increases from 0.15–0.32 (for z smaller than the impact coordinate) to asymptotically reach values comprised in the 0.82–0.89 range. These values agree fairly well with estimates based on operation of full-scale slagging gasifiers, where the fractional mass of ash issuing from the reactor in the wall phase is nearly 90%, at odds with a fractional mass of nearly 70% predicted at the design stage without consideration of near-wall particle accumulation effects. The departure of experimental data, for the *SP–SW* regime, from $y^{wall}=0$ at $z<0.13$ m is due to backmixing of the dispersed phase associated with recirculation and entrainment in the mainstream gas close to the oblique stagnation point located at $z=z^*$. Switching to the *NSP–NSW* interaction regime significantly affects wax partitioning. y^{wall} is systematically smaller along the reactor, approaching values of about 0.35. Even in this case, the fractional mass of wax at the wall is larger than 0, suggesting that wax is at least partly transferred to the near-wall segregated particle layer under the combined effect of the hydrodynamics of the confined multiphase flow, of particle adhesion/rebound and resuspension.

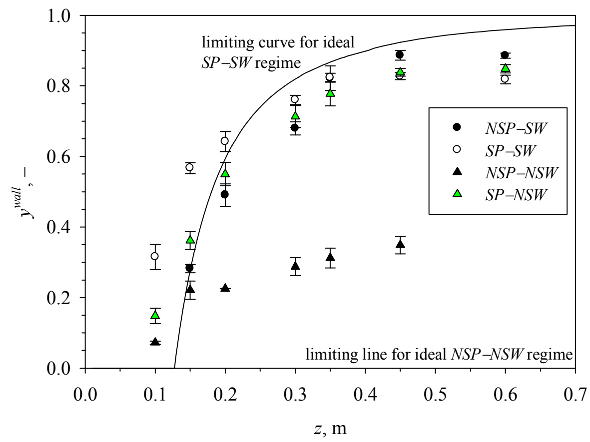

Figure 2. Axial profiles of the fractional mass of wax in the wall phase (y^{wall}) for the four interaction regimes.

Figure 3 reports the results obtained from the impact tests. The Pyrex and smooth wax surfaces (cases a and b) are shown as reference, where ε_n is about constant with v_{ni}. Moreover, the figure reports results obtained for the Pyrex target covered by: c–d) two wax powder layers with different thickness; e) a syrup layer spotted with wax powder. ε_n decreases in the presence of a powder layer, being smaller for a thicker powder layer. In particular, ε_n has a mean value equal to 0.28 for cases a and b, while it decreases to around 0.1 and 0.07 for cases c and d, respectively.

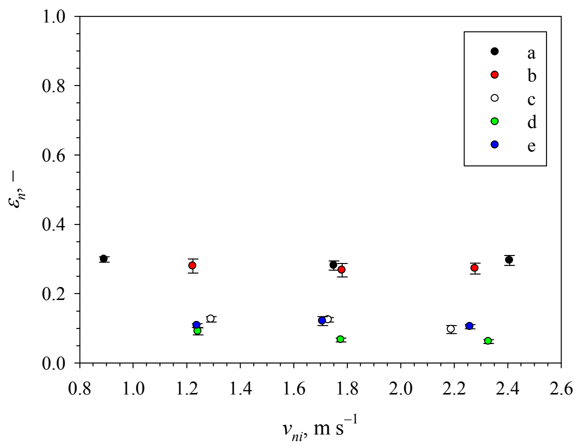

Figure 3. Effect of target surface on normal coefficient of restitution. a) Pyrex; b) Wax, smooth surface; c) Surface covered with 0.25 mm-thick layer of powdered wax; d) Surface covered with 1.4 mm-thick layer of powdered wax; e) Surface covered with syrup and 0.2 mm-thick layer of powdered wax.

These results are due to the presence of the powder layer which leads to a smaller equivalent elastic stiffness of the powder layer/target structure, a longer contact time, and a larger contact area. These features bring about larger dissipation due to adhesion force, hence smaller restitution coefficient. This applies also when increasing the thickness of the powder layer. Furthermore, the presence of a powder layer can emphasize energy dissipation due to wave propagation during particle–wall impact. It is remarkable that this reduction is the same regardless of whether a dry (Pyrex) or wet (syrup-layered Pyrex, case e) target is used. This finding may be explained since the powder layer separates the impinging particles from the wall substrates, and the particles partially penetrate the powder layer. These phenomena determine energy dissipation, hence smaller coefficients of restitution. This is very relevant to the assessment of the fate of char/ash particles in entrained-flow slagging gasifiers. Smaller restitution coefficients as the target is covered by a powder layer promote the establishment of segregation–coverage regimes which, in turn, may be responsible for the formation of a dense-dispersed phase in the near-wall zone [4].

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