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Wall effects in entrained particle-laden flows: The role of particle stickiness on solid segregation and build-up of wall deposits

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ABSTRACT

Particle–wall interaction is relevant to the performance of entrained-flow slagging gasifiers. Different micromechanical char–slag interaction patterns may establish, depending on the stickiness of the wall layer and of the impinging char particle. The main goal of this study is to improve the mechanistic understanding of particle–wall interactions, by using the tool of physical modeling. The idea behind this research campaign is to use molten wax as a surrogate of fuel ash. The wax had rheological/mechanical properties resembling those of a typical coal slag. Experiments have been carried out in a 0.10 m-ID lab-scale cold entrained-flow reactor, optically accessible, and equipped with a nozzle whence molten wax atomized into a mainstream of air. Reactor lengths in the range 0.1–0.6 m were investigated, while the wax was atomized at a temperature of 100–110 °C. Two interaction regimes were investigated: the “sticky wall–sticky particle” regime was simulated by setting the air mainstream and the wall temperatures at values beyond the wax melting range (160 °C and 140 °C, respectively); the “nonsticky wall–nonsticky particle” regime was simulated by setting both temperatures at 30 °C, i.e. well below the wax softening range. Assessment of the flow and segregation patterns was based on direct visual observation by means of a progressive scan CCD video camera, while the partitioning of the wax droplets into the different phases was characterized by their selective collection at the reactor exhaust. The micromechanics of particle–wall interactions in the “nonsticky–nonsticky” regime was analyzed on the basis of particle impact and of hydrodynamics of gas mainstream and jet flows. Threshold gas velocities for particle detachment were evaluated for the characterization of particle resuspension phenomena.

1. Introduction

Combustion and gasification under slagging conditions are key aspects of the design of modern entrained-flow reactors for thermal conversion of solid fuels, aimed at increasing the overall energy efficiency. In these systems, solid particles migrate toward the reactor walls, due to swirled/tangential flow induced in the reaction chamber and to turbophoresis, generating, thanks to the very high operating temperatures, a slag layer that flows along the reactor internal walls and is drained to the bottom of the reactor [1–6]. Understanding the phenomenology and proper design of slagging entrained-flow reactors requires the assessment of the fate of char particles as they impinge on the wall slag layer [7–10].

In a previous study, Montagnaro and Salatino [11] developed a phenomenological model that considers the establishment of a particle segregated phase in the near-wall region of the gasifier. In fact, it was highlighted that char particles impinging on the wall slag layer can either be entrapped inside the melt (a condition that hampers further progress of combustion/gasification), or adhere onto the slag layer's surface (progress of combustion/gasification is still possible in this case). 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 (that characterizes the entrained flow), so that the residence times of char particles are longer than the average gas space time, with a positive impact on carbon burn-off. Further studies, both experimental and theoretical, confirmed the soundness of this phenomenological framework [12–14].

Different micromechanical char–slag interaction patterns may establish, depending on the particle and the wall temperatures, on the solid/molten status of the particles impinging the slag layer or making up the slag itself, on the char conversion degree, on the particle kinetic energy, and on the surface tension [8,10,11,15]. In the present study,

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four different patterns are envisaged on the basis of the “stickiness degree” of the wall layer and of the impinging char particle:

- the material laying on the wall (prevailingly, inorganic ash) is “sticky” when the wall temperature is so high that ash is permanently kept in a 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 “nonsticky” char particles;
- the char particle is sticky when its temperature is beyond a critical value and the carbon conversion is beyond a given threshold, as the plastic behavior is emphasized when the content of refractory carbon decreases.

The four regimes are represented in Fig. 1: (*i*) sticky particle (*SP*) impinging on a sticky wall (*SW*); (*ii*) nonsticky particle (*NSP*) impinging on a sticky wall; (*iii*) sticky particle impinging on a nonsticky wall (*NSW*); (*iv*) nonsticky particle impinging on a nonsticky wall. Fig. 1 is complemented by Fig. 2, that shows how the different near-wall char–slag segregation regimes can occur along the reactor as carbon conversion increases. The fate of char particles depends on the complex mechanics of liquid–solid interphase interactions [1,3,11,16,17], that can determine rebound, splashing, coalescence, deposition, plunging, shattering, sticking and adhesion phenomena.

The present study lays along the path set by Troiano et al. [18] and aims at improving the mechanistic understanding of particle–wall interactions in entrained-flow systems, by using the tool of physical modeling. Particle–wall interactions are investigated in a lab-scale cold entrained-flow reactor, equipped with a nozzle whence molten wax atomized into a mainstream of air. The operating temperatures can be adjusted so as to tune the sticky–nonsticky behavior of both impinging wax droplets and wall layer. Assessment of flow and segregation patterns is based on a direct visual observation, as the reactor is optically accessible. The partitioning of the wax droplets/particles into the different phases is characterized by selective collection of ash leaving the reactor at the exhaust.

Troiano et al. [18] investigated the sticky wall–sticky particle (*SW–SP*) regime in a 0.04 m-ID reactor. They observed that the axial profiles of the fractional content of wax entrained in the dispersed phase closely conformed to values predicted by assuming idealized radial droplet trajectories in the jet and inertial impaction on the wall. In the present study the *SW–SP* regime is implemented in a larger reactor (0.10 m-ID) and the results are compared with those obtained in the *NSW–NSP* regime. A theoretical assessment of particle resuspension phenomena is developed for *NSW–NSP* regime, based on a quasi-static approach (force/moment balance), to determine threshold gas velocities that induce particle detachment from the wall surface.

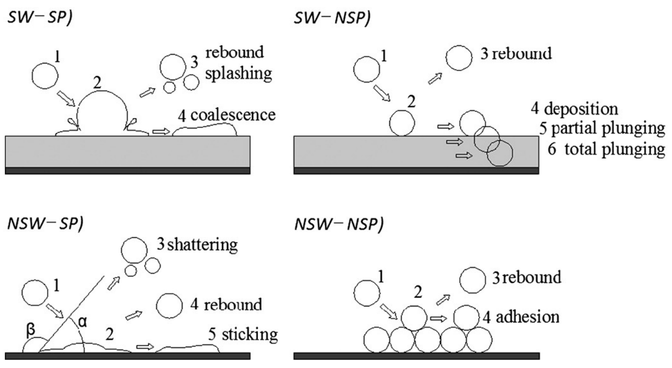

Fig. 1. Different micromechanical interaction patterns (*SW* stands for “sticky wall”, *SP* for “sticky particle”, *NSW* for “nonsticky wall” and *NSP* for “nonsticky particle”). (1) pre-impact, (2) impact, (3–6) post-impact.

2. Mechanistic background of particle adhesion and resuspension

Particle–wall interactions occurring during the *NSW–NSP* regime can be analyzed by considering the micromechanics of the impact of solid particles on a solid flat surface, on one side, and the mechanics of resuspension of attached particles from the wall, on the other.

Particle–wall collisions are generally characterized in terms of a restitution coefficient e, defined as the ratio between the rebound and the impact velocities. The coefficient takes the value $e = 1$ when the rebound is perfectly elastic, whereas $e \to 0$ when the particles dissipate their kinetic energy at the impact and adhere on the surface. The restitution coefficient embodies phenomena like elastic and plastic deformation of solid materials, surface contact forces and particle–wall friction. For collisions normal to a flat surface, the normal restitution coefficient is zero at impact velocities lower than a threshold value: the particles adhere on the surface as the impact energy is smaller than the adhesion energy [19]. The threshold impact velocity for particle capture, also called “capture velocity”, is a function of particle size and density, particle surface energy and elastic properties of both particle and surface (Young's moduli and Poisson's ratios) [20]. For impact velocity larger than the capture velocity, rebound occurs. For elastic materials the normal restitution coefficient tends to approach 1, whereas for elastic–plastic materials the restitution coefficient increases with the impact velocity as far as the material shows elastic behavior. When the impact velocity is further increased, plastic deformation begins, inducing additional energy losses during the impact and a decrease of the normal restitution coefficient. The limiting velocity, above which plastic deformation occurs, is determined by the bulk properties of the particles and the wall and is independent of particle size [19–21]. When an oblique impact is considered, particle–wall friction expressed by the tangential restitution coefficient has to be taken into account [22,23]. Moreover, particle rolling and sliding may be active in this case.

Once adhered to the wall, particles may eventually be resuspended under the action of gas flow in the near-wall region. When the hydrodynamic forces overcome adhesion, the particle is detached from the wall and eventually dragged into the bulk gas flow. Three different mechanisms of particle detachment from a wall surface, namely lift-off, sliding and rolling [24], can be considered on the basis of force balances along the normal and tangential direction of wall surface and of a moment balance on a particle embedded in a viscous sublayer, respectively [25–28]. The threshold velocity for particle detachment from a vertical flat surface can be calculated by considering:

- normal force balance (lift-off mechanism)

$$F_L = F_{PO} \tag{1}$$

- tangential force balance (sliding mechanism)

$$F_D + F_G = k_S(F_{PO} - F_L) \tag{2}$$

- moment balance (rolling mechanism)

$$1.4\frac{d_p}{2}F_D + \frac{d_p}{2}F_G > a(F_{PO} - F_L) \tag{3}$$

where F_L is the lift force, F_{PO} the adhesion force, F_D the drag force and F_G the force due to gravity. Furthermore, k_s is the static coefficient of friction (a coefficient of 0.6 can be assumed), d_p is the particle diameter and a the contact radius between the particle and the surface. In the moment balance equation (Eq. (3)), the factor 1.4 accounts for the non-uniformity of the flow field [29]. F_L may be calculated as reported by Ziskind et al. [25] and Leighton and Acrivos [30] for a particle fully embedded in the viscous sublayer. F_{PO}, also called pull-off force, may be defined as the opposite of the force required to separate two bodies and it can be calculated according to the JKR model [31], revised for a rough