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Research article

Multiphase flow patterns in entrained-flow slagging gasifiers: Physical modelling of particle–wall impact at near-ambient conditions

Maurizio Troiano [a], Roberto Solimene [b,*], Piero Salatino [a], Fabio Montagnaro [c]

[a] Dipartimento di Ingegneria Chimica, dei Materiali e della Produzione Industriale, Università degli Studi di Napoli Federico II, Piazzale Vincenzo Tecchio 80, 80125 Napoli, Italy
[b] Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche, Piazzale Vincenzo Tecchio 80, 80125 Napoli, Italy
[c] Dipartimento di Scienze Chimiche, Università degli Studi di Napoli Federico II, Complesso Universitario di Monte Sant'Angelo, 80126 Napoli, Italy

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ABSTRACT

Particle–wall interaction phenomena relevant to multiphase flow in entrained-flow slagging coal gasifiers have been investigated. The micromechanical patterns of particle impingement on the reactor walls have been characterized in a model system by high speed imaging and tracking of wax particles impacted onto a flat surface at near-ambient conditions. The solid/plastic versus fluid state of the wax particles was controlled by proper selection of the particle, ambient and target temperatures. Particle–wall collision was described in terms of normal and lateral restitution coefficients and capture efficiency. The influence of the particle stickiness, impact velocity and angle, and surface properties and structure of the target on the rebound patterns was studied. Results indicate that the elastic–plastic adhesive model provides an adequate representation of the non sticky particle–wall collisions. Moreover, the presence of a powder layer on the target favours energy dissipation and accumulation of particles close to the surface. This pattern promotes the establishment of a dense-dispersed phase in the near-wall zone of entrained-flow slagging gasifiers. Increasing the temperature, particles shift from the solid/plastic to the fluid state and the coefficient of restitution drops to vanishingly small values, confirming that deposition is the prevailing phenomenon during the collision of sticky particles on a wall.

1. Introduction

Entrained-flow gasification (EFG) keeps an important role in the current portfolio of solid fuel conversion technologies. EFG outperforms most competing technologies from the standpoints of overall energy conversion efficiency and emission control. Moreover it provides adaptive and flexible routes toward integration of energy conversion with fuel and chemical synthesis and/or CO_2 capture.

Entrained-flow gasifiers are characterized by short residence times (in the order of a few seconds), hence, very fine particle sizes and high temperatures are required to allow a good conversion. High temperatures ensure the destruction of tars. Unburnt carbon is vanishingly small if the time-temperature history of the fuel particles and oxidizing/reducing conditions are properly tuned by careful control of multiphase flow in the gasification chamber. Most industrial EF gasifiers operate in the slagging mode: fuel particles migrate toward the reactor walls, mainly due to swirled/tangential flow and “turbophoresis” promoted in the reaction chamber. Bulk-to-wall migration of solids results, thanks to the very high operating temperatures, into the build-up of a slag layer of molten ash, which flows along the reactor internal walls and is eventually drained at the bottom of the gasification chamber [1–6].

The performance of slagging EF gasifiers may be critically affected by the fate of char/ash particles as they interact with the wall slag layer [7–10]. Montagnaro and Salatino [11] developed a phenomenological model, which considers the establishment of a particle segregated phase in the near-wall region of the gasifier. Char particles impinging on the wall slag layer can either be entrapped inside the melt, or adhere onto the slag layer's surface. The first scenario is unlikely to occur, on the basis of forces and energy balances governing char/slag interaction [7,11], along with particle impact velocities and trajectories throughout the gasifier [12]. On the other hand, if particles adhere onto the slag layer's surface, further carbon conversion is possible. When the slag layer is extensively covered by char particles, further entrapment of particles is prevented, and a densely dispersed segregated particle cloud may establish in the close proximity of the wall ash layer. This annular phase moves slower than the lean particle-laden gas phase, hence, particle residence times in this region are longer than the average gas space-time. This feature is responsible for enhanced carbon conversion. The soundness of this phenomenological framework has been confirmed by experimental and theoretical studies [13–15].

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,

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* Corresponding author.
E-mail address: solimene@irc.cnr.it (R. Solimene).

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char conversion degree, particle kinetic energy, surface tension of the slag layer, particle effective stiffness and char/slag interfacial tension [8,10,11, 16]. Char–slag interaction patterns are hereby classified 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 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, which is inherently refractory, is reduced.

On the basis of this classification, four interaction scenarios establishing during EF gasification can be considered, namely: (i) non sticky char/ash particle 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*).

Mechanistic understanding of particle–wall interactions in EF systems for *SP–SW* and *NSP–NSW* regimes has been recently undertaken by Troiano et al. [17,18], using the tool of physical modelling. They investigated the particle–wall interactions in a lab-scale cold EF reactor, equipped with a nozzle, whence molten wax could be atomized into a mainstream of air. Operating temperatures were adjusted so as to tune the sticky–non sticky behaviour of both impinging wax droplets and wall layer. Furthermore, both laminar and turbulent gas flow conditions were applied. The assessment of flow and segregation patterns was obtained by the selective collection of wax at the exhaust of the reactor, and by image analysis and particle tracking. Their findings confirmed that particle deposition and segregation are enhanced by particle stickiness and turbulence.

The relationship between particle deposition and slagging has been extensively addressed in previous studies. According to Baxter [19,20], ash deposition rate under inertial conditions is proportional to the particle capture efficiency, which in turn depends on ash stickiness and the properties of the surface against which particles are impacted. For synthetic and alkali-rich ash, the stickiness criterion is verified when the weight fraction of the liquid phase in the particle is nearly 15% [21,22]. Bool and Johnson [23] studied the ash deposition behaviour during coal combustion in an EF reactor. Ash collection efficiencies on a deposition probe sharply increased to a maximum as char burnout approached a critical value, to slightly decrease thereafter. This result confirms that the effective ash stickiness depends on its residual carbon content. Furthermore, the sharp rise in the stickiness indicates a change in the structure of the particles around the critical char burnout, from porous and non sticky char, to molten sticky slag. Whitty and co-workers [24] studied the transition from char to slag for a bituminous coal using a laminar EF reactor under oxidizing conditions. In the initial stage of coal oxidation (the initial stage of char–slag transition), minerals are still encapsulated in the residual refractory carbon matrix, and the char particle is non sticky. At intermediate to large particle conversion (the middle stage of the transition), encapsulated minerals begin to appear on the external surface of the char and they melt, increasing the effective stickiness of the char particle. At even larger particle conversion (the final stage of the transition), the included minerals are released, forming molten slag. This char—slag transition occurs at a conversion degree $X_C \approx 90\%$ [24], provided that the temperature exceeds the ash melting point.

Several empirical methods, for instance slagging indices, ash sticking temperatures and viscosity models, were proposed in the literature to determine particle sticking criteria [25–27]. The modified "Urbain Model" is widely used to model the viscosity of coal ash on the basis of the acid-to-base ratio and can be coupled with other criteria to determine the fate of char particles in entrained-flow reactors [26]. The temperature at which the amorphous slag transforms into a crystalline phase is used to calculate the critical viscosity. Therefore, for particle viscosity lower than the critical value (namely, at higher temperatures), the particle sticks. The drawback of these viscosity models to predict particle sticking is that they do not take into account the effect of residual carbon on particle stickiness and the stickiness of the target wall. The modified "Urbain Model" can be coupled with other criteria to describe the behaviour of char/slag interaction in entrained-flow reactors [16,28].

The fate of char/ash particles in the near-wall region of EFG is better predicted by detailed mathematical and physical modelling. Particle–wall interactions can be investigated and described in terms of a coefficient of restitution (the ratio between the rebound and the impact velocities). Dong et al. [29] investigated the normal restitution coefficient of fly ash particles impacting on a planar surface at room temperature. Pisupati and co-workers [30] carried out EF and drop experiments at ambient conditions to simulate the different particle–surface collision patterns relevant to EFG. The restitution coefficient is an important parameter when modelling multiphase flow in the gasification chamber, e.g. by the tools of CFD-DPM, as it critically affects the boundary condition for particle–wall collisions.

The aim of the present study is the characterization of the coefficient of restitution during impact experiments of particles at different stages between solid/plastic to fluid conditions. Despite targeted at characterizing the dynamics of particle–wall interaction in EF slagging gasifiers, a physical modelling approach was followed, by simulating the real process with synthetic wax particles impacted against a target at near-ambient conditions. The influence of the stickiness of the particles and of the target surface, of the impact velocity, of the impact angle as well as of the material and structure of the target were investigated.

2. Theoretical background of particle–wall collision

Particle–wall collisions are generally characterized in terms of a restitution coefficient ε, defined as the ratio between the rebound and the impact velocity. The coefficient takes the value $\varepsilon = 1$ when the impact is perfectly elastic, whereas $\varepsilon \to 0$ when the particles dissipate all their kinetic energy at the impact and adhere on the surface. The restitution coefficient embodies phenomena like elasto–plastic deformation and viscoelastic behaviour (energy loss due to wave propagation) of solid materials, surface contact forces and particle–wall friction. Different particle–wall impact models are reported in literature [31–35]. Among them, the model developed by Thornton and Ning [36] seems to be sufficiently accurate to describe the normal impact of fine particles, such as fly ash, onto a planar surface, as reported by Dong et al. [29]. This model takes into account adhesion effects during the normal impact of elastic–perfectly plastic spheres. In their model, 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 [33]. This critical velocity, also called "capture" or "sticking" velocity, v_s, is a function of particle size and density, particle surface energy and elastic properties of both the particle and surface (Young's moduli and Poisson's ratios) [36], as follows:

$$v_s = 1.84\left[\frac{4\left(\frac{2\Gamma}{d_p}\right)^5}{3\rho_p^3K^2}\right]^{\frac{1}{6}} \tag{1}$$

where Γ is the surface energy at the interface, d_p and ρ_p are the particle diameter and density, respectively, and K is the composite Young's modulus, expressed as:

$$K = \frac{4}{3}\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)^{-1} \tag{2}$$