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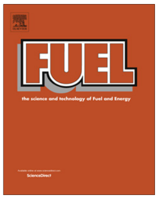

Full Length Article

Impact experiments of char and ash particles relevant to entrained-flow coal gasifiers

Maurizio Troiano [a,*], Tommaso Santagata [a], Fabio Montagnaro [b], Piero Salatino [a], Roberto Solimene [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] Dipartimento di Scienze Chimiche, Università degli Studi di Napoli Federico II, Complesso Universitario di Monte Sant'Angelo, 80126 Napoli, Italy
[c] Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche, Piazzale Vincenzo Tecchio 80, 80125 Napoli, Italy

HIGHLIGHTS

- Particle–wall interactions were characterized by impact experiments.
- Coal, char with different carbon conversion and ash particles were used.
- Experimental tests were carried out in cold and hot conditions.
- The target material and surface affect the tangential restitution coefficient.
- The restitution coefficients decrease with carbon conversion.

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ABSTRACT

The present study addresses particle–wall interaction phenomena relevant to entrained-flow coal gasifiers. The dynamics of coal, char and ash particles as they are impacted onto a flat surface in cold and hot conditions and undergo momentum transfer and rebound, has been characterized by means of high speed imaging and tracking. Particle–wall collisions were described in terms of normal, tangential and global restitution coefficients. The influence of carbon conversion, impact velocity and surface properties and structure of the target on the dynamical pattern of rebound has been scrutinized. The results indicate that, even at ambient conditions, some plastic deformation occurs during the impact. The restitution coefficients decreased as temperature and carbon conversion increased. This feature was more pronounced at large carbon conversion, confirming the criticality of the char/slag transition to particle deposition on the wall. The dissipation of momentum associated with particle impact may promote the establishment of a dense-dispersed phase in the near-wall zone of entrained-flow slagging gasifiers.

1. Introduction

Entrained-flow gasification is a versatile technology which provides an attractive route to the exploitation of a variety of solid fuels, either alone or in combination, along paths that include energy conversion and/or production of chemicals [1–3]. Moreover it provides a route for pre-combustion CO_2 capture.

In entrained-flow gasifiers (EFG), very fine particles react with gaseous oxidants within a short residence time (in the order of a few seconds). Most industrial EF gasifiers operate at high temperatures which promote the onset of slagging of ash residues. These operating temperatures ensure the destruction of tars and oils and, if the gasifier is appropriately designed and operated, warrant very high degrees of carbon conversion [4]. Furthermore, EFG have become the preferred technology for hard coals and have been selected for the majority of commercial-sized IGCC applications.

The ash behaviour plays a key role in the performance of entrained-flow gasifiers. Above the softening point, ash becomes sticky and agglomerates causing blockage of the beds or fouling of the heat exchange equipment. Once above the slagging temperature (about 1300–1500 °C), ash has a fully liquid behaviour: hence, it is easily drained from the bottom of the gasifier and is eventually quenched (most typically in a water bath) as coarse and fine slag [3,5–10]. Both coarse and fine slag may have a relatively large content of unburned carbon [4,11,12]. Ash residues further contribute to the fly slag, which leaves the gasifier with the syngas [6]. The presence of unburned carbon within the slag is a result of the incomplete gasification of the coal, which is the major determinant of the gasification efficiency in EF processes.

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[*] Corresponding author.
E-mail address: maurizio.troiano@unina.it (M. Troiano).

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Nomenclature

C_{CO}	concentration of carbon monoxide [ppm]
d	diameter [m]
F	molar flow rate [mol h^{-1}]
f	momentum ratio [–]
M_C	molecular weight of carbon [g mol^{-1}]
Q	volumetric flow rate [m^3 h^{-1}]
R_a	mean roughness [μm]
T	temperature [°C]
t	time [s]
v	velocity [m s^{-1}]
W_C	carbon mass [g]
x	parallel-to-wall coordinate [m]
X_C	fractional conversion of carbon [–]
y	normal-to-wall coordinate [m]

Greek symbols

α	angle [°]
ε	coefficient of restitution [–]

Subscripts

g	global
i	impact
n	normal
p	particle
r	rebound
t	tangential

Superscripts

$*$	dimensionless
0	initial time

Furthermore, fly ash not captured within the slag can contribute to fouling on the surface of the pipes in the convective syngas coolers [13]. One advantage of a slagging reactor over a non-slagging one relies on the higher economic value of the collected slag compared with bottom ash, because of its longer durability and resistance to surface wear. In addition, the slag layer results in a molten protective coating and reduces wear and heat loss at the wall, contributing to increase the cold gas efficiency of the gasifier [14]. However, uncontrolled build-up of the slag layer can bring about plugging. Moreover, excessive slag deposition on the membrane walls reduces the overall heat-transfer coefficient. The relationship between particle deposition and slagging has been widely investigated in previous studies. In particular, the rate of ash deposition under inertial conditions was found to be proportional to the efficiency of particle capture which in turn depends on ash stickiness and properties of the surface against which the particles are impacted [15,16]. The behaviour of ash deposition in a coal gasifier was also investigated by using a laminar drop tube furnace [17,18]. The results showed that the rate of ash deposition increased with both increasing temperature of the deposit surface and gasification temperature. Bool and Johnson [19] investigated the behaviour of ash deposition during coal combustion in an EF reactor. The efficiency of ash collection on a deposition probe sharply increased to a maximum as the 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 [20].

Several empirical methods, such as slagging indices, ash sticking temperatures and viscosity models, were proposed in the literature to determine particle sticking criteria [10,21,22]. 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 [21]. 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 shortcoming of these viscosity models as tools for the prediction of particle sticking is that they do not take into account the effect of residual carbon on stickiness of particle and target wall. The modified “Urbain Model” can be coupled with other criteria to describe the behaviour of char/slag interaction in EF reactors [13,14].

The performance of slagging EFG may be critically affected by the fate of char/ash particles as they interact with the wall slag layer [11,23–30]. Montagnaro and Salatino [31] proposed a phenomenological model which considers the establishment of a particle segregated phase in the near-wall region of the gasifier. This annular phase moves slower than the lean particle-laden gas phase: hence the particle residence time in this region is longer than the average gas space-time. This feature is beneficial to enhanced carbon conversion. The mechanistic understanding of particle–wall interactions in EF systems has been recently investigated, using the tool of physical modelling, in a lab-scale cold EF reactor equipped with a nozzle whence molten wax could be atomized into a mainstream of air [32,33]. The experimental findings confirmed that particle deposition and segregation are enhanced by particle stickiness and turbulence.

In spite of several numerical studies on the behaviour of particles and slag in EFG [14,26,34,35], the fate of char/ash particles in the near-wall region of EFG still lacks accurate predictive tools based on mathematical and physical modelling of particle–wall interaction. Different micromechanical patterns can occur, depending on parameters such as particle and wall temperatures, solid/molten status of particles and wall layer, degree of char conversion, particle kinetic energy, surface tension of the slag layer, particle effective stiffness and char/slag interfacial tension [14,24,26,31]. The recent literature has investigated and described particle–wall interactions in terms of a coefficient of restitution (the ratio between the rebound and the impact velocities). The restitution coefficient is an important parameter in the context of multiphase flow modelling of the gasification chamber, e.g. by the tools of CFD-DPM, as it critically affects the boundary condition for particle–wall collisions. In this framework, Dong et al. [36] investigated the normal restitution coefficient of fly ash particles impacting on a planar surface at room temperature, while Pisupati and co-workers [37] carried out EF and drop experiments at ambient conditions to simulate the different patterns of particle–surface collision relevant to EFG. Recently Troiano et al. [38] investigated, by particle–wall impact experiments, the restitution coefficient and the capture efficiency varying particle stickiness, surface wall properties and impact angle and velocity under nearly ambient conditions. However the rebound characteristics of coal particles, especially in hot conditions, are still lacking.

The aim of the present study is to characterize the dynamics of coal particle rebound in terms of coefficient of restitution during non-orthogonal particle–wall impact in experiments carried out with coal batches pre-gasified to different degrees of carbon