PARTICLE-WALL IMPACT EXPERIMENTS FOR ENTRAINED-FLOW BIOMASS GASIFIERS

M. Troiano*, F. Montagnaro, R. Solimene***, P. Salatino***
maurizio.troiano@unina.it
*Dipartimento di Ingegneria Chimica, dei Materiali e della Produzione Industriale, Università degli Studi di Napoli Federico II, Piazzale V. Tecchio 80, 80125 Napoli (Italy)
**Dipartimento di Scienze Chimiche, Università degli Studi di Napoli Federico II, Complesso Universitario di Monte Sant'Angelo, 80126 Napoli (Italy)
***Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche, Piazzale V. Tecchio 80, 80125 Napoli (Italy)

Abstract
Particle–wall interaction phenomena relevant to entrained-flow biomass gasifiers have been investigated. The dynamics of char and ash particles as they are impacted onto a flat surface in hot conditions has been characterized by means of high speed imaging and tracking. Two types of biomass have been investigated, i.e. wood chips and corn stover. Particle–wall collisions were described in terms of normal, tangential and global coefficients of restitution. The influence of carbon conversion and impact velocity on the dynamical pattern of rebound and deposition has been investigated. The results indicate that the global restitution coefficient for char and ash particles is well below 1, suggesting that some plastic deformation occurs upon impacts. Furthermore, ash of wood chips is not prone to form a slag layer, while ash of corn stover extensively contributes to formation of ash deposits and melts. The dissipation of momentum associated with particle impact promotes the establishment of a dense-dispersed phase in the near-wall zone of entrained-flow slagging gasifiers.

1. Introduction
The use of biomass represents one important element toward a sustainable energy production in the near-future, allowing a substantial reduction of net CO_2 emissions, while providing energy reliably and weather-independent. Gasification is a very efficient way of converting the chemical energy embedded in biomass and one of the best alternatives for deriving energy and basic chemicals from waste carbonaceous solids [1]. In entrained-flow gasifiers (EFG), fine particles react with gaseous oxidants within a short residence time (in the order of a few seconds). Most industrial EFGs operate at high temperatures (slagging mode) to guarantee a tar-free syngas and high carbon conversion [2]. The ash behaviour plays a key role in the performance of EFGs. Above the softening point, ash becomes sticky and agglomerates causing blockage of the bottom bed at the discharge or fouling of the heat exchange equipment. Once above the slagging temperature, ash has a fully liquid behaviour and it is easily drained from the bottom of the gasifier and

quenched as vitrified slag. 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. However, uncontrolled build-up of the slag layer can cause refractory corrosion and plugging. The rate of ash deposition under inertial conditions depends on ash stickiness and properties of the surface against which the particles are impacted. Furthermore, for coal particles, the effective ash stickiness depends on its residual carbon content. Empirical methods, such as slagging indices, ash sticking temperatures and viscosity models, initially proposed for coal, are used for biomass to determine particle sticking criteria [2]. Further studies on ash formation, deposition and char/slag interaction are still needed.
The performance of slagging EFG may be critically affected by the fate of char/ash particles as they interact with the wall slag layer. Montagnaro and Salatino [3] proposed a phenomenological model which considers the establishment of a particle segregated phase in the near-wall region of the gasifier. This annular phase is characterized by a longer residence time than the average gas space-time, a feature beneficial to enhanced carbon conversion. Further studies confirmed the soundness of this phenomenological framework [4]. The recent literature has investigated particle–wall interactions in terms of a coefficient of restitution (the ratio between the rebound and the impact velocities), as it critically affects the boundary condition for particle–wall collisions in the context of multiphase flow modelling of the gasifier. The restitution coefficient of normal and oblique impacts at room and hot temperature conditions has been investigated to simulate the different patterns of particle–surface collision relevant to coal EFG [5–8]. No data are available for the rebound characteristics of biomass particles. The aim of the present study is to characterize the impact-deposition-rebound dynamical patterns of biomass particles in terms of coefficient of restitution during non-orthogonal particle–wall impacts. Experiments were carried out with batches of wood chips and corn stover particles pre-gasified to different degrees of carbon conversion, while varying the impact velocity.

2. Methodology

The characterization of the rebound behaviour of particles in EF slagging gasifiers is not trivial. Non-spherical char particles at different carbon burn-off are impacted onto confining walls covered by either a dry refractory material or a slag layer. Furthermore, the particle stickiness deeply affects the interaction behaviour as a consequence of the variation of particle mechanical properties with temperature and residual carbon content. In this study impact tests were carried out to evaluate the rebound/deposition behaviour of biomass particles upon collision with a planar surface. Two types of biomass fuels were considered, wood chips (woody biomass) and corn stover (straw from agricultural and herbaceous biomass). The particle–wall collisions are characterized in terms of a restitution coefficient ε, defined as the ratio between the rebound and the impact velocity. The restitution coefficient embodies phenomena like elasto–plastic deformation, viscoelastic behaviour of solid materials, surface contact forces and particle–wall friction. It is useful to define a normal, tangential and global coefficient of restitution, ε_n, ε_t, and ε_g, respectively as:

$$\varepsilon_n = \frac{-v_{n,r}}{v_{n,i}}; \quad \varepsilon_t = \frac{v_{t,r}}{v_{t,i}}; \qquad \varepsilon_g = \frac{v_r}{v_i} = \sqrt{\frac{\frac{v_{n,r}^2}{v_{n,i}^2}}{sin^2\,\alpha_i} + \frac{\frac{v_{t,r}^2}{v_{t,i}^2}}{cos^2\,\alpha_i}} = \sqrt{\varepsilon_n^2\,sin^2\,\alpha_i + \varepsilon_t^2\,cos^2\,\alpha_i} \qquad (1)$$

where v_n and v_t represent the components of the velocity in the normal and tangential directions, respectively, while the subscripts i and r are referred to the impacting and rebound phase, respectively. ε_g tends to ε_n for large impact angles (α_i →90°) and to ε_t for small impact angles (α_i →0°).

3. Experimental

Particle–wall micromechanical interactions were investigated by means of the experimental apparatus shown in Fig. 1. The test rig consisted of a Carbolite vertical tubular furnace equipped with a PID system for temperature control, an alumina tube (1.5 m-height and 0.056 m-ID) inserted in the furnace and a hot impact chamber connected to the alumina tube at the bottom of the upper vertical furnace. The impact chamber was designed and built-up to guarantee the desired temperature and to enable direct optical access to the impact zone. The optical access was ensured by a quartz window, sandwiched by refractory slabs to ensure a good insulation. Three shielded R-type thermocouples were used to monitor the gas temperature: in the alumina tube, in the pre-impact zone and close to the target.

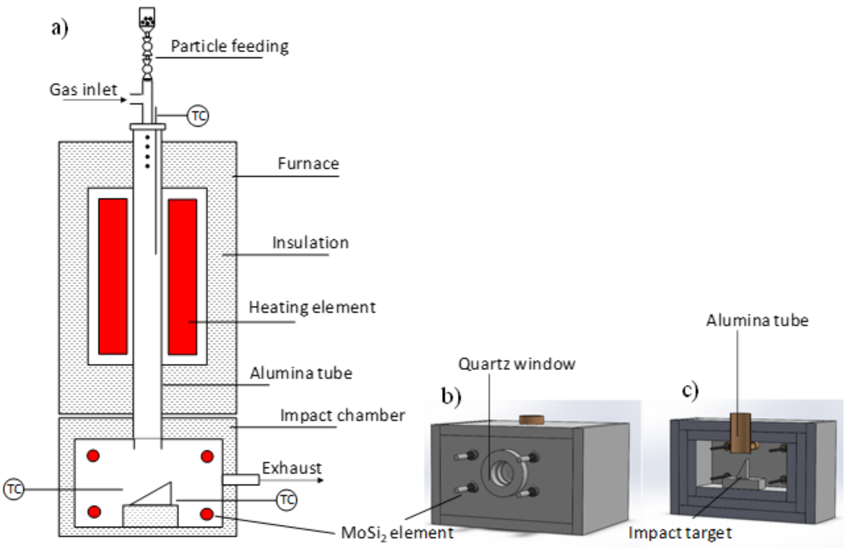

Figure 1. Experimental test rig. a) Outline of the apparatus; b) Impact furnace; c) Section of the impact furnace.

Batches of micron-sized particles (150–180 μm) were fed at the top of the alumina tube by means of two on/off valves, and entrained along the tube by a stream of nitrogen fed at the top of the furnace at ambient temperature. The particles are entrained by the mainstream gas flow along the reactor. The particle impact velocity was controlled by regulating the main nitrogen flow rate. When the particles left the tube, they impacted on a target plate located in the impact chamber about 0.05 m below the tube (Fig. 1b-c)). The target was shaped to establish particle impact angles around 60° with respect to the horizontal [6]. Particle velocities before and after the impact were determined experimentally by image analysis, hence the restitution coefficient was calculated. Details of the image post-processing technique are reported elsewhere [7,8]. Two types of biomass were investigated, i.e. wood chips and corn stover. Table 1 reports proximate and ultimate analyses for the two fuels. Ash mineral analysis was also carried out. The ratio of species which form low-melting compounds (Si+P+K-based, wt %) to the species with high fusion temperature (Ca+Mg-based, wt %) was 0.7 for wood chips and 4.7 for corn stover. To investigate the effect of carbon conversion, impact experiments were carried out in nitrogen environment using particles pre-converted at different degrees of carbon burn-off. Raw particles were sieved in the range d_p=165±15 μm and pyrolyzed in a vertical tubular furnace at 750°C in nitrogen. After pyrolysis, char particles underwent CO_2 gasification at 900°C for different reaction times to obtain char particles with different residual carbon content.

Table 1. Proximate and ultimate analyses of wood chips and corn stover.

	Wood chips		**Corn stover**	
Proximate analysis	***As-received (wt%)***	***Dry (wt%)***	***As-received (wt%)***	***Dry (wt%)***
Moisture	15.3	0.0	9.3	0.0
Volatile Matter	63.9	75.4	69.8	77.0
Ash	1.7	2.0	4.0	4.4
Fixed Carbon	19.1	22.6	16.9	18.6
Ultimate analysis	***As-received (wt%)***	***Dry (wt%)***	***As-received (wt%)***	***Dry (wt%)***
Carbon	44.2	53.3	42.8	49.4
Hydrogen	6.42	7.7	6.1	7.1
Nitrogen	0.4	0.5	0.5	0.6
Sulphur	0.1	0.1	0.1	0.1
Chlorine	0.1	0.1	0.2	0.2
Ash	1.7	2.0	4.0	4.4
Moisture	15.3	0.0	9.3	0.0
Oxygen	31.8	36.3	37.0	38.2
HHV (MJ kg^{-1})	**–**	**21.1**	**–**	**17.8**

The experimental tests aimed at characterizing the phenomenology of particle–wall interaction in terms of restitution coefficients. Experiments were performed in hot conditions (1400 °C) using as target material the raw refractory that was coated with a high temperature cement and then polished. The rebound characteristics of char particles with different residual carbon content (X_C=0.28, 0.45, 0.9 for wood chips and X_C=0.12, 0.5, 0.9 for corn stover) and of ash particles were investigated. Coefficients of restitution and deposition efficiency were measured at fixed impact angle (60°) while varying the particle impact velocity (0.3–2.3 m s^{-1}).

4. Results and discussion

Experimental data for the coefficient of restitution are reported as values averaged over multiple tests (symbols). Bars corresponding to the standard error are also reported. To ensure experimental reproducibility, each point is the average of at least 30 measurements. The rebound characteristics of char particles at different degrees of carbon conversion and ash particles are hereby reported and discussed. The effect of the global impact velocity $v_{g,i}$ on the global restitution coefficient ε_g is shown in Fig. 2a) and b) for wood chips and corn stover, respectively. The values of ε_g are always smaller than unity, suggesting that plastic deformations occur as the mechanical properties change with increasing temperature. For both the biomass types, ε_g is nearly constant with the impact velocity and it decreases for ash particles. This result highlights that for both the biomasses the char/slag transition occurs only when all the carbon is consumed, i.e. for a carbon conversion equal to 100%, while for Illinois coal particles enhanced deposition was recorded when carbon conversion reached a value around 90% [8]. For wood chips particles (Fig. 2a)) the global coefficient of restitution is around 0.35 for char particles and around 0.2 for ash particles, while for corn stover (Fig. 2b)) it is around 0.3 for char and lower than 0.05 for ash.

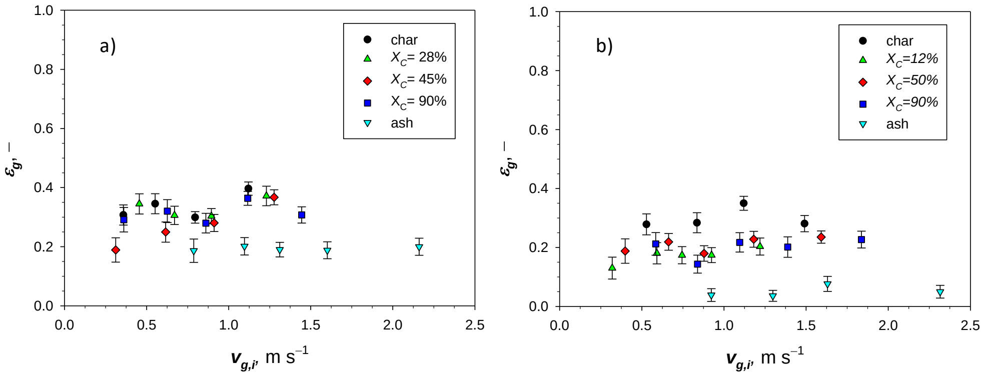

Figure 2. Effect of the global impact velocity on the global coefficient of restitution for char with different carbon conversion and ash particles of a) wood chips; b) corn stover. Operating conditions: T=1400°C, α_i=60±10°.

These results highlight that wood chips ash is not prone to form extensive deposits and a stable molten layer on the wall upon the impact. It is possible to relate the slagging tendency of wood chips char and ash to the ratio of species which are likely to form low-melting compounds (Si+P+K-based, wt %) to the species with high fusion temperature (Ca+Mg-based, wt %). In terms of the corresponding oxides, this ratio is around 0.7 for wood chips ash, consistent with limited tendency to slagging reported also in the literature [9]. The formation of high-temperature melting compounds, such as CaO, and the lack of Ca silicates which have a relatively low melting temperature [9] are responsible for this behaviour. On the contrary, corn stover ash particles, characterized by a different ash composition, display much larger propensity to deposition and formation of a stable molten layer, as confirmed by the high ratio (Si+P+K)/(Ca+Mg) which is about 4.6.

References

[1] Tijmensen, M.J.A., Faaij, A.P.C., Hamelinck, C.N., van Hardeveld, M.R.M., "Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification", *Biomass Bioenergy* 23: 129–152 (2002).

[2] Higman, C., van der Burgt, M., *Gasification 2nd edition*, Gulf Professional Publishing, 2008.

[3] Montagnaro, F., Salatino, P., "Analysis of char-slag interaction and near-wall particle segregation in entrained-flow gasification of coal", *Combust. Flame* 157: 874–883 (2010).

[4] Troiano, M., Salatino, P., Solimene, R., Montagnaro, F., "Wall effects in entrained particle-laden flows: the role of particle stickiness on solid segregation and build-up of wall deposits", *Powder Technol.* 266: 282–291 (2014).

[5] Dong, M., Li, S., Xie, J., Han, J., "Experimental studies on the normal impact of fly ash particles with planar surfaces", *Energies* 6: 3245-3262 (2013).

[6] Gibson, L.M., Gopalan, B., Pisupati, S.V., Shadle, L.J., "Image analysis measurements of particle coefficient of restitution for coal gasification applications", *Powder Technol*. 247:30-43 (2013).

[7] Troiano, M., Solimene, R., Salatino, P., Montagnaro, F., "Multiphase flow patterns in entrained-flow slagging gasifiers: physical modelling of particle–wall impact at near-ambient conditions", *Fuel Process. Technol.* 141: 106-116 (2016).

[8] Troiano, M., Santagata, T., Montagnaro, F., Salatino, P., Solimene, R., "Impact experiments of char and ash particles relevant to entrained-flow coal gasifiers", *Fuel* 202: 665-674 (2017).

[9] Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G., "An overview of the chemical composition of biomass", *Fuel* 89: 913-933 (2010).