Fuel 209 (2017) 674–684

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Experimental characterization of particle-wall interaction relevant to entrained-flow gasification of biomass

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ARTICLE INFO

Keywords:
Particle–wall interaction
Entrained flow
Molten ash
Impact test
Restitution coefficient
Deposition efficiency

ABSTRACT

The present study addresses particle–wall interaction phenomena relevant to entrained-flow gasifiers. Two types of biomass have been investigated, i.e. wood chips and corn stover. The dynamics of char and ash particles as they are impacted onto a flat surface in cold and hot conditions has been characterized by means of high speed imaging and tracking. Particle–wall collisions were described in terms of normal, tangential and global coefficients of restitution as well as deposition efficiency. The influence of carbon conversion and impact velocity on the dynamical pattern of rebound and deposition has been investigated. The results indicate that, even at ambient conditions, some plastic deformation occurs during the impact. Experiments performed under hot conditions demonstrate that a drop of the coefficients of restitution takes place at high temperature, especially at low impact velocity, for both the tested biomasses. This feature can be explained by considering the change of mechanical properties of particles as the temperature increases, and the effect of the adhesion energy during the impact. Results highlighted that 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 under hot conditions. Results from experiments with corn stover indicate that char particles deposit onto the molten ash surface. 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 world's energy demand is constantly increasing, with fossil fuels —coal, natural gas, and oil— still being the main primary energy sources. The use of biomass represents a major route toward sustainable production of energy in the near-future as it should at least partly replace fossil fuels. Biomass can be converted either directly to heat and electricity or transformed to gaseous and liquid fuels [1,2]. Combustion, pyrolysis and gasification are the three main pathways to thermochemical conversion of carbonaceous fuels. The net efficiency for electricity generation from biomass combustion is usually low, ranging from 20 to 40% [3]. Biomass co-firing in existing combustors is usually limited to 5–10% of the total feedstock owing to concerns about management of fuel feeding systems and fouling of heat transfer surfaces [4]. Pyrolysis converts biomass into bio-oil, biochar and non-condensable gases [5]. Bio-oil has a great potential in terms of energy density and dispatchability, but is difficult to utilize directly owing to its high acidity and oxygen content. Hence, downstream processing of bio-oil is most often necessary and may hamper more widespread application of biomass pyrolysis [6]. Gasification is one of the most efficient ways of converting the chemical energy embedded in biomass and one of the best alternatives for deriving energy and basic chemicals from waste carbonaceous solids [7–9]. Strict requirements on purity of produced syngas can be managed by selecting gasification technologies and operating conditions that yield relatively clean syngas, particularly with a low content of tar, and/or by setting up efficient gas cleaning methods.

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 [10–13]. Moreover, it provides a route for pre-combustion CO_2 capture. Different technologies of entrained-flow gasification apply to biomass at commercialized or at an advanced development stage [14]. 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 EFG operate at high temperatures

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http://dx.doi.org/10.1016/j.fuel.2017.08.044
Received 1 May 2017; Received in revised form 24 July 2017; Accepted 8 August 2017

Nomenclature

C_{CO}	concentration of carbon monoxide [ppm]
d	diameter [m]
$D.E.$	deposition efficiency [−]
F	molar flow rate [mol h^{-1}]
M_C	molecular weight of carbon [g mol^{-1}]
N	number [−]
Q	volumetric flow rate [m^3 h^{-1}]
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

0	initial time
tot	total

which promote the onset of slagging of ash residues. These operating temperatures are able to guarantee a tar-free syngas and, if the gasifier is appropriately designed and operated, very large degrees of carbon conversion and low carbon-in-ash [15].

Ash behaviour plays a key role in the performance of EFG. 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: hence, it is easily drained from the bottom of the gasifier and is eventually quenched as coarse and fine slag [12,16–21]. Both coarse and fine slag may have a relatively large content of unburned carbon [15,22–24]. In addition, solid residues leave the gasifier as fly ash entrained by syngas [17]. The presence of unburned carbon within the slag/fly ash is a result of the incomplete gasification of coal, which is the major determinant of the gasification efficiency in EF processes. Furthermore, fly ash not captured within the slag can contribute to fouling on the surface of the pipes in the convective syngas coolers [25]. A slagging reactor has an advantage in the higher economic value of the collected slag compared with bottom ash of non-slagging reactor, 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 [26]. However, uncontrolled build-up of the slag layer can cause refractory corrosion and 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, especially for coal applications. In particular, the rate of ash deposition under inertial conditions depends on ash stickiness and properties of the surface against which the particles are impacted [27,28]. Furthermore, the deposition rate increases with both increasing temperature of the deposit surface and gasification temperature [29,30]. For coal particles, the effective ash stickiness depends on its residual carbon content [31]. Furthermore, the sharp rise in stickiness indicates a change in the structure of the particles around a critical char burnout, from porous and non-sticky char to molten sticky slag [32].

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 [33]. Further studies aimed at characterizing the thermo-physical and chemical properties of ash at high temperatures, ash fusion temperatures and thermodynamics of slag behaviour [34–37]. Further studies on ash formation, deposition and char/slag interaction are still needed [38].

The performance of slagging EFG may be critically affected by the fate of char/ash particles as they interact with the wall slag layer [22,38–45]. Montagnaro and Salatino [46] 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 [47]. The mechanistic understanding of particle–wall interactions in EF systems has been recently investigated in a lab-scale cold EF reactor equipped with a nozzle whence molten wax could be atomized into a mainstream of air, using the tool of physical modelling [48,49]. 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 [26,41,50,51], 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 slag layer, particle effective stiffness and char/slag interfacial tension [26,39,41,46]. 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 gasifier, e.g. by the tools of CFD-DPM, as it critically affects the boundary condition for particle–wall collisions. In this framework, the restitution coefficient of normal and oblique impacts at room temperature has been investigated to simulate the different patterns of particle–surface collision relevant to EFG [52–54]. Recently Troiano et al. [55] investigated, by particle–wall impact experiments, the restitution coefficient for non-orthogonal impacts varying particle stickiness, surface wall properties and impact velocity for Illinois coal particles under cold and hot temperature conditions. The increasing interest in using biomass as a feedstock for energy applications requires a deep knowledge of the interaction of biomass particles with the walls of combustors/gasifiers. However, to the authors' knowledge, no data are available for the rebound characteristics of biomass particles, both at ambient and high temperature conditions.

Based on such considerations, the present study contributes to the characterization of the impact-deposition-rebound dynamical patterns of biomass particle in terms of coefficient of restitution and deposition efficiency during non-orthogonal particle–wall impact. Experiments were carried out with batches of particles pre-gasified to different degrees of carbon conversion (from char to ash). Experiments were carried out in both cold and hot conditions for two biomasses, i.e. wood