Powder Technology 247 (2013) 30–43

Contents lists available at ScienceDirect

Powder Technology

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

Image analysis measurements of particle coefficient of restitution for coal gasification applications

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ARTICLE INFO

Article history:
Received 7 December 2012
Received in revised form 21 May 2013
Accepted 2 June 2013
Available online 21 June 2013

Keywords:
Coefficient of restitution
Equancy
Particle rotation

ABSTRACT

New robust Lagrangian computational fluid dynamic (CFD) models are powerful tools that can be used to study the behavior of a diverse population of coal particle sizes, densities, and mineral compositions in entrained gasifiers. By using this approach, the responses of the particles impacting the wall were characterized over a range of velocities (1 to 8 m/s) and incident angles (90 to 20°). Within CFD models, the kinematic coefficient of restitution is the boundary condition defining the particle wall behavior. Four surfaces were studied to simulate the physical conditions of different entrained-flow gasification particle–surface collision scenarios: 1) a flat metal plate 2) a low viscosity silicon adhesive, 3) a high viscosity silicon adhesive, and 4) adhered particles on a flat metal plate with Young's modulus of elasticity ranging from 0.9 to 190 GPa. Entrained flow and drop experiments were conducted with granular coke particles, polyethylene beads and polystyrene pellets. The particle normal and tangential coefficients of restitution were measured using high speed imaging and particle tracking. The measured coefficients of restitution were observed to have a strong dependence on the rebound angles for most of the data. Suitable algebraic expressions for the normal and the tangential component of the coefficient of restitution were developed based upon ANOVA analysis. These expressions quantify the effect of normalized Young's modulus, particle equancy, and relative velocity on the coefficient of restitution. The coefficient of restitution did not have a strong dependence on the particle velocity over the range considered as long as the velocity was above the critical velocity. However, strong correlations were found between the degree of equancy of the particles and the mean coefficient of restitution such that the coefficient of restitution decreased for smaller particle equancies. It was concluded that the degree of equancy and the normalized Young's modulus should be considered in applications such as gasification and other cases involving the impact of non-spherical particles and complex surfaces. Sliding was observed when particles impacted on oblique surfaces; however, the resulting effects were within the range of measurement uncertainties.

1. Introduction

To meet energy demand at an economical cost, power plants try to attain the maximum carbon conversion possible based on plant design. The Integrated Gasification Combined Cycle (IGCC) plant has proven to be more thermally efficient than pulverized coal combustion. As a gasifier of interest, the high capacity of the entrained flow type is made possible by the relatively low residence time of coal particles within the gasifier (0–4.5 s). In entrained flow gasifiers, fine coal concurrently reacts with steam and oxidant. Entrained flow gasifiers use oxygen as the oxidant and operate at high temperatures well above the critical temperature for slag formation. These conditions are set to ensure high carbon conversion. However, when coal is not completely converted, part of the heating value is lost. This loss in heating value translates to a loss in the heating value of the syngas and thus lower plant efficiency. To resolve this issue, fly ash captured in the radiant syngas cooler sump is recycled. The energy recovered from recycled fly ash is partially offset by auxiliary power used in producing additional oxygen to consume the carbon [1]. Furthermore, additional additive and water must be added along with the recycled fly ash with carbon to maintain a low viscosity of the mixture to help the atomization of the slurry. Carbon conversion also correlates with the amount of fly ash within the syngas [1]. Fly ash not captured within the slag or the sump can contribute to fouling through ash deposition on the surfaces of the pipe in convective syngas coolers [1]. Excess char deposition in convective coolers leads to unplanned shutdowns until the convective pipes are cleared of ash deposits. Ash deposition also leads to a reduction in heat transfer both in the radiative (slagging) section and in the low temperature convective (fouling) heating sections resulting in equipment downtime (or loss in electrical generation). Therefore, there is a need to control ash deposition and the

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0032-5910/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.powtec.2013.06.001

Nomenclature

C	damping coefficient
e	coefficient of restitution
E	potential energy, J
f	impulse ratio
f_0	circumferential tension of the adhesion force per unit length, N/m
K	stiffness, N/m
m	mass of a particle, g
r_0	axis of zero velocity, cm
R	coefficient of restitution absent of adhesion
v	velocity, cm/s
W	work of adhesion, J
Y	modulus of elasticity, GPa
Y'	normalized modulus of elasticity, GPa

Greek symbols

α	angle, radians
η	ratio of the tangential velocity to the normal velocity
ρ	the ratio of the rebound adhesion impulse to the rebound elastic impulse
ϕ	degree of equancy
ω	angular velocity rad/s

Subscripts

A	adhesion
c	critical
H	Hertzian
i	impacting
IC	instantaneous center
n	normal
p	particle
r	rebounding
R	roughness
t	tangential direction
T	terminal
x	Cartesian coordinate, x-direction
y	Cartesian coordinate, y-direction

handling of slag disposal. This has led towards the development of models for particle sticking.

Of all empirical methods to determine the threshold for particle sticking, such as slagging indices and ash sticking temperatures, viscosity models have been the most widely used. The modified Urbain Model [2] is a commonly used to empirically model viscosity of coal ash based on the acid to base ratio. Typically, the temperature of critical viscosity (the temperature where slag transforms from a glassy Newtonian phase to a crystalline Non-Newtonian phase) is empirically determined. This temperature is then used within the viscosity models to determine the critical viscosity. The probability of the particle sticking for temperatures below the critical value is then based on the ratio of the predicted viscosity of the particle at a given particle temperature to the critical viscosity. Therefore, the closer the value of the particle viscosity is to the critical viscosity, the less likely the particle is to stick and vice versa. However, the main pitfall of relying on viscosity models to predict particle sticking is that it only takes the ash composition into consideration. Char particles that have a significant amount of carbon may not have enough ash on the surface to influence sticking [3]. Furthermore, viscosity models are still approximate when applied to different coals and they do not take into account the wall conditions such as a slag laden gasifier surface or cooled adhered particles. They cannot be used for particle tracking purposes to predict the magnitude and direction of particles that are predicted to rebound from the surface as are needed in CFD that models are potentially powerful tools to better elucidate fly ash formation mechanisms.

Past efforts in developing modeling tools to characterize ash deposition include the efforts of Rushdi et al. and Ma et al. [4,5]. For the mechanistic tool described by Rushdi, a subroutine was implemented to determine the particle shift temperature for the particle viscosity. The slagging and prediction tool developed by Ma et al. to assess slagging and fouling depends on empirically determined inputs for the sticking efficiency and ash impaction rate. Both efforts were largely based on the characterization of ash behavior and did not address the physics behind the tendency of particles to adhere or rebound. One such model has been proposed by Shimizu and Tominaga, who assume that the gasifier temperature is higher than the melting point of ash [6]. In the model, unreacted char is assumed to be captured by the slag surface, and to rebound from the surface where char has adhered. The probability for the char capture rate is based on the rate of the surface area covered by the unreacted char and total surface area. However, the basis of this probability contradicts experimental work of authors who have shown the poor wettability of slag and carbon [7–10] and empirical evidence that the probability of adhesion only increases with increasing carbon conversion [3]. Wang et al. [11], have utilized a model developed by Lee et al. [12] to predict adhesion of char particles and predict slag layer thickness on the wall of a combustor. However, the model of Lee et al. was based on the empirical results of Tabkoff's and Malak's experiments for the coefficient of restitution for ash particles at ambient conditions [13]. The model of Lee assumed a molten layer surrounding a solid ash particle. However, under high temperature conditions, char particles are described as viscoelastic.

A more physics based approach to determining particle deposition is to track the trajectories of char particles within an entrained flow gasifier and evaluate ash deposition for each particle wall impact. A Discrete Phase Model (DPM) is of interest since the gas phase is treated as a continuum phase while the particles are treated as a discrete phase. Such a tool could be utilized not only to identify particles by their carbon conversion but also to track particles that could be proven to be problematic through the probability of rebounding from the slag. Within the Discrete Phase Model, the kinematic coefficient of restitution (the ratio of the rebound velocity to the impacting velocity) is the relevant boundary condition for the particle wall behavior. The objective of this paper is to determine the wall boundary conditions for particle wall collisions for the CFD DPM Modeling of coal. By determining these conditions, the influence of carbon in addition to the ash in char can be assessed. Therefore, it is necessary to assess contact models which can incorporate the influence of carbon in addition to ash.

One of the earliest theories involving particle wall impact is the Hertz Theory in which a frictionless punch impacts a half space in the absence of an adhesion force [14]. The JKR theory improved upon the Hertz Theory by including adhesion forces in the vicinity of the contact area and balancing the elastic energy with the mechanical and surface energy of the impact [15]. An alternative theory by Derjaguin, Muller, and Toporov, called the DMT Theory, was developed for a rigid sphere and plane in which adhesion forces act in the annular zone around the contact zone [16]. Tabor developed a dimensionless parameter representing the ratio between the gap outside the contact zone and the equilibrium distance between atoms to indicate the applicability of the JKR Hertz Model versus the DMT Model [17]. The Hertz maximum contact area and Hertzian indentation depth are employed in the Brach and Dunn Model for elastic impact [18,19]. Models for inelastic impact also assume a Hertzian Profile for the contact radius [20]. Meanwhile, for inelastic impact, three phases are presumed for particle wall impact; elastic loading, plastic loading, and elastic unloading [20–22]. Such models depend on the yield strength and hardness of the particle.