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Particle–wall interaction in entrained-flow slagging coal gasifiers: Granular flow simulation and experiments in a cold flow model reactor

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ABSTRACT

Entrained-flow slagging coal gasifiers display large conversion efficiencies and small levels of unconverted carbon at the exhaust. Both features are apparently at odds with the fairly small "space-time" of the particle-laden gas feeding, as compared with the time scale of heterogeneous gasification of carbon. This apparent inconsistency can be explained by considering that fuel residence times are longer than the "space-time" due to segregation of fuel particles in the near-wall region of the gasifier. Segregation is promoted by swirl flow, by particle–wall interaction as the wall is covered by a molten layer of slag and by the establishment of a dense-dispersed flow of granular solids in the proximity of the wall.

This study presents results of granular flow simulations of the interaction of a dense-dispersed particle flow with the confining wall. Simulations consider that both the particles and the wall may be either "sticky" or "non sticky", based on the prevailing elastic vs plastic behaviour upon collision. The effect of drag forces exerted on particles by swirled gas flow is simulated in a simplified manner. Particle–particle collisions are modelled with a Hertzian approach that includes torque and cohesion. The extent and time scale of segregation of a lump of particles loaded into a cylindrical vessel are assessed. Results clearly indicate the different structure of the layer of particles establishing at the wall surface in the different interaction regimes.

Results of simulations are qualitatively compared with results of an experimental campaign performed in a reactor representing a cold flow model of the entrained-flow gasifier, where solid, molten or semi-molten particles have been simulated by atomized wax as surrogate material. Altogether, the results confirm the importance of the particle–particle and particle–wall micromechanical interactions for a correct prevision of the segregation of fuel particles in entrained-flow slagging gasifiers.

1. Introduction

The relevance of the slagging conditions and of the fate of char particles as they interact with the confining walls to the performance of entrained-flow gasifiers is now widely recognized (Shimizu and Tominaga, 2006; Montagnaro and Salatino, 2010; Ni et al., 2011; Li and Whitty, 2012; Chen and Ghoniem, 2013; Chen et al., 2013; Gibson et al., 2013; Duchesne et al., 2014; Ding et al., 2015; Hosseini and Gupta, 2015; Shen et al., 2015, 2016; Ye and Ryu, 2015). Hydrodynamic instabilities leading to the establishment of a core–annulus flow pattern have been frequently observed in gas–solid downers (Zhu et al., 1995; Cao and Weinstein, 2000; Zhang et al., 2003) and in the simulation of coal fired swirled combustors (Shang and Zhang, 2009). In particular, particle clustering, consisting of loosely packed particles moving in the same direction as the bulk flow, has been observed at the wall region of downers (Zhao et al., 2010; Chalermsinsuwan et al., 2013). Particle migration towards the wall and segregation in the near-wall region of vertical channels have been observed in dilute particle-laden turbulent flows (Marchioli and Soldati, 2002; Marchioli et al., 2007; Monchaux et al., 2012; Mallouppas and van Wachem, 2013; Zonta et al., 2013; He and Wang, 2015). Particle clustering in the near-wall region emphasizes the importance of

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List of symbols

A [m^2]	contact surface
a [–]	parameter defined in Eq. (22)
a^* [$m\,s^{-2}$]	parameter defined in Eq. (24)
c [$kg\,m^{-1}\,s^{-2}$]	cohesion energy density
d [m]	displacement
F [$kg\,m\,s^{-2}$]	force
G [$kg\,m^{-1}\,s^{-2}$]	shear modulus
H [m]	height of the cylindrical chamber
I [$kg\,m^2$]	moment of inertia
i [–]	unit versor
k [$kg\,s^{-2}$]	stiffness
K^* [–]	normalized total particle kinetic energy
m [kg]	mass
n [–]	number
n_u [–]	normal unit vector
Q [$m^3\,h^{-1}$]	air flow rate
R [m]	radius
R_c [m]	radius of the core cylinder
r [m]	radial position
r' [m]	radial position at which the volume forces are vanished
S [$kg\,s^{-2}$]	parameter defined in Eqs. (13) and (14)
T [$kg\,m^2\,s^{-2}$]	torque
T_a [°C]	atomization temperature
T_{ms} [°C]	mainstream temperature
T_w [°C]	wall temperature
t [s]	time
u [$m\,s^{-1}$]	particle velocity
v [$m\,s^{-1}$]	relative velocity
W [$g\,s^{-1}$]	mass flow rate of wax
Y [$kg\,m^{-1}\,s^{-2}$]	Young's modulus
y [–]	fractional mass of wax
z [m]	axial distance from the atomizing nozzle

Greek letters

β [–]	parameter defined in Eq. (12)
γ [$kg\,s^{-1}$]	viscoelastic damping constant
Δ [m]	distance from wall defined in Eq. (23)
δ [m]	particles overlap
ε [–]	restitution coefficient
μ [–]	friction coefficient
ν [–]	Poisson's ratio
ρ [$kg\,m^{-3}$]	particle density
Ω [$rad\,s^{-1}$]	angular velocity of a rotating frame
ω [$rad\,s^{-1}$]	rotational velocity

Superscripts

*	equivalent
lean	referred to the lean-dispersed phase
wall	referred to the wall phase

Subscripts

a	atomization
c	contact
coh	cohesion
i, j	generic particles
ms	mainstream
n	normal
p	particle
r	rolling
rad	radial
rel	relative
s	static
t	tangential
V	volume

multiparticle interaction. This may become the dominant effect to the point that particle motion approaches the characteristics of a granular flow. Few studies can be found in the literature exploring the dynamics of an incipient dense particle layer near a wall induced by the strong inertial impingement of heavy particles. Methods are available to implement the 4-way coupling necessary to model interactions between particles and fluids in dense-dispersed flows (see Deen et al., 2012). However, the computational effort limits their application to a small number of particles. Useful approximations can be obtained by introducing simplifying assumptions. Dilute-to-dense particle flow transitions were effectively simulated in the study of cyclones (Chu et al., 2009), dense riser flows (Breault et al., 2008; Shah et al., 2011), dust lifting from walls (Kosinski and Hoffmann, 2007). Sommerfeld (2003) analyzed the effect of wall roughness on particle distribution, showing the strong influence of wall properties. The effect of particle–particle collisions in the modulation of gas flow turbulence in a swirled chamber (Liu et al., 2011) and on the distribution of particles (Gui et al., 2010) was investigated as well. Nonetheless, the effect of the level of energy dissipation during the contact among particles or between particles and confining walls has been hardly taken into account.

Previous theoretical and experimental studies by the same research group (Montagnaro and Salatino, 2010; Montagnaro et al., 2011; Ambrosino et al., 2012, 2013) were directed to relate the establishment of a particle segregated phase in the near-wall region of the gasifier to micromechanical patterns of particle–wall interaction, considering the effect of the wall slag layer. In co-current downward entrained-flow slagging gasifiers (Fig. 1), char particles impinging on the wall slag layer can either be entrapped inside the melt (a condition that hampers the further progress of combustion/gasification), or adhere onto the slag layer's surface (the progress of combustion/gasification is still possible in this case). In the latter case, and if the slag layer is extensively covered by char particles, a dense-dispersed particle segregated phase may establish in the close proximity of the wall ash layer, where the excess impinging char particles, that cannot be accommodated on the slag surface, accumulate. This annular phase moves slower than the mainstream, so that the residence times of char particles are longer than the average gas space-time, with a positive impact on the carbon burn-off. The mechanism of particle–wall interaction in entrained-flow systems has been scrutinized by the same group using the tool of physical modelling (Troiano et al., 2014a, b, 2016): particle–wall interactions were investigated in a lab-scale cold entrained-flow reactor, equipped with a nozzle whence molten wax was atomized into a mainstream of air. Different micromechanical char–slag interaction patterns may establish, depending on particle and wall temperatures, on the solid/molten status of the particles impinging the slag layer or making up the slag itself, on char conversion degree, on particle kinetic energy, on surface tension. These can be reduced to four basic interaction patterns, depending on the "degree of stickiness" of the wall layer and of the impinging char particle (Yong et al., 2012; Troiano et al., 2014a, b, 2016). The material laying on the wall (prevailingly, inorganic ash) is "sticky" when the wall temperature is so high that ash is permanently kept in a 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. On the other hand, the char particle is sticky when the carbon conversion is beyond a given threshold, as the plastic behaviour is emphasized when the content of refractory car-