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Modeling the slag layer in solid fuel gasification and combustion – Formulation and sensitivity analysis

Sze Zheng Yong [a],*, Marco Gazzino [b], Ahmed Ghoniem [a]

[a] Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA
[b] ENEL Ingegneria e Innovazione S.p.A., 56122 Pisa, Via Andrea Pisano 120, Italy

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ABSTRACT

A steady-state model has been developed to describe the flow and heat transfer characteristics of the slag layer in solid fuel gasification and combustion. The model incorporates a number of sub-models including one for particle capture, and takes into consideration the temperature and composition dependent properties of slag, the contribution of momentum of captured particles and the possibility of slag resolidification. An equally important issue is the interaction of the particles colliding with the slag layer. High inertia particles tend to rebound whereas slower particles are trapped in the slag layer. Since only trapped particles are relevant to the slag layer build-up, a particle capture criterion for colliding particles is introduced. The model predicts the local thickness of the molten and the solid slag layers, the average slag velocity, the temperature distribution across the layer and the heat flux to the coolant, taking into account the influence of molten and resolidified slag layers coating the combustor or reactor wall.

1. Introduction

Solid fuels and in particular, coal contain inorganic mineral matter. When burned, the inorganic compounds form an incombustible ash residue. In most coal boilers and reactors, coal ash is captured from the flue gas chimneys in the form of fly ash or removed from the combustor bottom as bottom ash. When operating the combustor above the ash fusion temperature, coal ash melts. Some of these molten particles are deposited along the wall, forming a slag layer that flows along the internal walls of the combustion chamber. This molten slag is collected from a molten ash port located at the downstream end of the combustor. The layer of molten slag can act as a thermal barrier to protect the combustor walls. However, because of wall cooling, a portion of this molten slag may resolidify, clogging the molten ash port. Therefore, to maintain a free passage at the molten ash port, understanding the behavior of slag is an integral part of reactor design process.

Several models have been proposed to predict slag formation and its flow characteristics in entrained-flow gasifiers. Seggiani [1] has proposed an analytical time-dependent slag accumulation and flow model to predict both the solid and molten slag layer thicknesses for the gasifier of the IGCC plant in Puertollano, Spain. As an extension to that model, Bockelie et al. [2] introduced a numerical scheme for predicting the molten layer thickness. Similarities in both models include the assumptions of negligible shear stress at the slag surface and a linear temperature profiles across both the solid and molten slag layers. Wang et al. [3] used an approach similar to that of Seggiani [1] but included an important feature, that is, the influence of particle deposition on the slag flow momentum. However, Wang et al.'s work stopped short of applying energy conservation to predict the slag temperature, and hence could not predict resolidification.

Suggestions have also been made that particles may more readily captured by a reactor wall that is covered by molten slag layer than in the case of uncovered walls. A model that is able to predict the probability of capture but does not differentiate between particles of different sizes and velocities was given in Shimizu and Tominaga [4]. Benyon [5] has earlier asserted that a crude check of the capture criterion be made based on the angle and velocity of the particle impact. Alternatively, Tominaga et al. [6] suggested that the criterion be based on the viscosities of the slag and incoming particles at the time of collision. Montagnaro and Salatino [7] has confirmed using order of magnitude estimates that the plunging and overlaying of particles are not likely to occur but did not provide a conclusive capture criterion. In contrast, Emory and Berg [8] brought up the role of a vapor film between the particle and slag layer which introduced another element of complication. A simple but more encompassing capture criterion is necessary.

In this paper, we combine the models described in Seggiani [1] and Wang et al. [3]. Moreover, an energy balance is derived for the steady-state case, and a cubic temperature profile across the molten slag layer is used to replace the linear temperature profile assumed in Seggiani [1]. A slag capture criterion is proposed in Section 2.2. The criterion involves determining the stickiness of the slag layer and the impacting particles. This sub-model

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* Corresponding author.
E-mail address: szyong@mit.edu (S.Z. Yong).

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Nomenclature

Symbols

c_p	slag specific heat (J/kg K)
$c_{p,p}$	particle specific heat (J/kg K)
d_p	particle diameter (m)
D	combustor diameter (m)
g	gravitational constant (m/s^2)
G_s	gravity contribution to slag flow (kg/m^4 s)
h_{melt}	particle heat of fusion (J/kg)
h_o	convective heat transfer coefficient to coolant (W/m^2 K)
j	current computational cell index (–)
k	slag thermal conductivity (W/m K)
k_{wall}	wall thermal conductivity (W/m K)
k_{sld}	solid slag thermal conductivity (W/m K)
$\dot{m}''_d$	local particle deposition flux (kg/m^2 s)
$\dot{m}'_{ex}$	cell mass flow rate/unit length (kg/m s)
$\dot{m}''_f$	local particle feeding flux (kg/m^2 s)
$\dot{m}''_{melt}$	particle phase change flux (kg/m^2 s)
$\dot{m}''_{rb}$	local particle rebound flux (kg/m^2 s)
$\dot{m}'''_{vc}$	particle volumetric consumption/devolatilization rate (kg/m^3 s)
M_p	momentum contribution to slag flow (kg/m^4 s)
q_{in}	heat flux to the slag surface (W/m^2)
q_{loss}	heat loss to coolant (W/m^2)
$Q'_{ex,j}$	cell heat transfer rate/unit length (W/m)
T_c	coolant temperature (K)
T_{cv}	temperature at critical viscosity (K)
T_{int}	interface temperature (K)
T_{gas}	bulk gas temperature (K)
T_p	particle temperature (K)
T_s	slag surface temperature (K)
T_{wi}	internal wall temperature (K)
T_{wo}	outer wall temperature (K)
u_{avg}	local average slag velocity (m/s)
u_p	particle velocity in the direction of slag flow (m/s)
v_p	particle velocity in the direction normal to slag flow (m/s)
z	distance from the slag surface (m)

Greek letters

α	reactor inclination from the horizontal (°)
δ	total slag thickness (m)
δ_l	molten slag thickness (m)
δ_{sld}	slag thickness (m)
δ_{wall}	wall thickness (m)
Δx	cell slag surface length (m)
μ_s	slag viscosity (Pa s)
ρ_p	particle density (kg/m^3)
ρ_s	slag density (kg/m^3)
σ_{sp}	slag-particle surface tension (N m)
σ_p	particle-air surface tension (N m)
σ_s	slag-particle surface tension (N m)
τ_p	average shear stress on slag surface (Pa)
θ	contact angle (°)

deterministically predicts the particles that are captured, as opposed to the probabilistic sub-model used in Wang et al. [3] which was based on Shimizu and Tominaga [6].

2. Slag model

The slag model is developed to better predict the wall boundary condition of a CFD framework for modeling coal combustion or gasification (see Fig. 2). The combustor or gasifier simulation supplies the slag model inputs: the local per unit area particle feeding rate $\dot{m}''_f$, the particle temperature T_p, the particle velocity in the direction of slag flow u_p, the slag density ρ_p and the per unit area heat flux to the slag surface q_{in}. The slag model computes the slag surface temperature, T_s, that is fed back as the wall boundary condition for the next CFD iteration, as well as the average slag velocity, u_{avg}, the molten and solid slag thickness, δ_l and δ_{sld}, the inner and the outer wall temperatures, T_{wi} and T_{wo}, the mass flow rate per unit length, $\dot{m}''_{ex}$, and the per unit area heat flux to the coolant, q_{loss}. For the slag model, the wall properties and the wall cooling conditions must be supplied and these inputs include the wall thermal conductivity k_{wall}, the wall thickness δ_{wall}, the heat transfer coefficient to the coolant h_o and the coolant temperature T_c. Iterations between the CFD solution and the slag model are performed with every particle phase calculation of the reactor until steady-state is achieved in both fluid and particle phases.

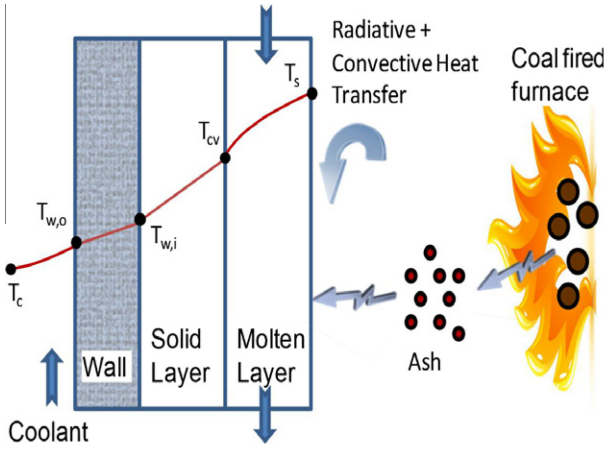

Fig. 1. Mass and heat transfer to reactor wall.

The slag model employs an Eulerian approach which uses the readily defined CFD mesh cells. For each control volume or cell, computations are performed using an analytical model to reduce computational time. Therefore, the accuracy of this model is dependent on the CFD mesh resolution along the reactor walls.

2.1. Slag flow model

The slag flow model is based on mass, energy and momentum conservation using the following assumptions:

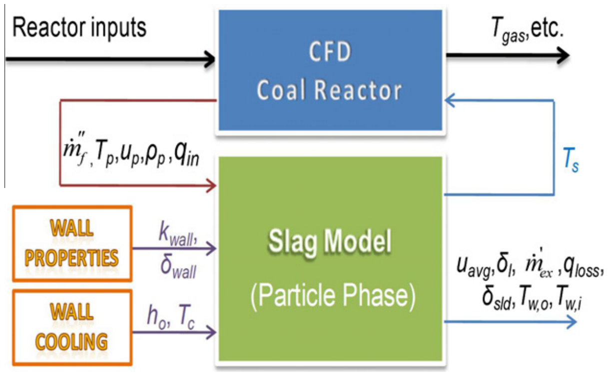

Fig. 2. Slag model in CFD framework.