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Numerical modeling of slag flow and heat transfer on the wall of an entrained coal gasifier

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HIGHLIGHTS

- New numerical model was proposed for slag flow and heat transfer in coal gasification.
- The model was compared to analytical models under exemplary operating conditions.
- Results revealed limitations of existing models and the reasons in their formulation.
- The model can overcome such limitations and incorporate various property submodels.

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ABSTRACT

In an entrained coal gasifier, coal ash turns into molten slag which deposits on the walls to form solid and liquid slag layers. It is important to understand the slag behavior to prevent the blockage of slag tap and maintain the desired level of heat absorption on the wall. In this study, we proposed a comprehensive numerical model to predict the flow and heat transfer characteristics of the slag layers. The model can be used as the wall condition for detailed computational fluid dynamic or process simulations of the gasifier.

The numerical model was evaluated in comparison with existing analytical models for a commercial coal gasifier under three exemplary operating conditions. The new model adequately predicted the thickness, velocity, and temperature of the slag layers, as well as the heat flux to the wall. Under particular operating conditions that had discrepancies between the model predictions, the reasons were discussed in relation to the respective model formulation and assumptions/simplifications introduced. It was shown that the temperature profile within the liquid slag was close to a linear relationship at sufficiently high gas temperatures, while it became parabolic when the gas temperature fell below T_{cv}. Applying the analytical models requires caution under the conditions in which the assumptions on the temperature profile are not valid. The numerical model can be applied to various operating conditions without such limitations and be extended to incorporate different slag property submodels.

1. Introduction

Coal gasification is a versatile technology for producing fuels, chemicals, and/or energy by converting the solid fuel into CO- and H_2-rich syngas. In many commercial gasification processes, entrained flow reactors with dry or slurry feeding of pulverized coal are employed for compact and complete conversion. Given that gasifiers typically operate at very high temperatures (~1500 °C) and high pressures (20–60 bar) [1,2], advanced technologies are required to design the reactor system and monitor/control various parameters for stable operation.

The behavior of coal ash is associated with key issues in the design and operation of a gasifier, as well as the syngas treatment process. During high-temperature gasification, coal ash turns into molten slag at temperatures well above the melting point. A significant fraction of the molten slag is deposited onto the wall which is cooled by water/steam passing through membrane tubes covered with a refractory lining. Because of the low temperature at the wall, the slag initially solidifies; subsequently, with the continuous build-up of the slag layer, newer deposits maintain their liquid state and flow downward by gravity. The viscosity at the interface between the layers of the flowing and stagnant liquid slags is referred to as the critical viscosity [3–5], which is typically 25 Pa s [1]. Because the slag viscosity depends strongly on the temperature, the temperature at the critical viscosity (T_{cv}) is a critical

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Nomenclature

A	area facing the adjacent cell, m^2
a	coefficient
b	coefficient
C	specific heat of the slag, J/kg/K
F	cross-sectional area perpendicular to the slag flow
g	gravity, 9.81 m/s^2
H	enthalpy, J/s
ΔH	enthalpy of reaction, J/s
h	convection coefficient, $W/m^2/K$
Δh	specific enthalpy of reaction, J/kg
k	thermal conductivity, W/m/K
M	momentum, kg m/s^2
m	mass flow rate, kg/s
Q	heat transfer rate, W
q	heat flux, W/m^2
R	radius from the cylindrical axis
r	radius perpendicular to the wall, m
T	temperature, K
U	overall heat transfer coefficient, $W/m^2/K$
V	volume, m^3
v	streamwise velocity, m/s
Y	height along the cylindrical axis, m
y	length parallel to the wall, m
z	coordinate for the thickness of the liquid slag layer starting from the gas-slag interface, m
Greek	
α	angle from the horizontal plane, °
δ	thickness of a slag layer, m
ε	emissivity
μ	viscosity, Pa s
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant
ϕ	variables
χ	under-relaxation factor
Subscript	
C	coolant (water/steam)
cond	conduction
conv	convection
cv	critical viscosity
dep	depositing slag
gas	gas
GL	from gas to liquid slag
I	innermost control volume facing the gas
i	index for a control volume within the liquid slag layer
in	inflow from the section above
J	number of sections in the streamwise direction
j	index for a section of slag layer in the streamwise direction
L	liquid slag
LS	from liquid slag to solid slag
out	outflow to the section below
R	refractory
RC	from refractory to coolant
react	reactions of residual carbon or the phase transformation
ref	reference
S	solid slag
SR	solid slag to refractory
surf	liquid slag surface facing syngas
tube	membrane water wall tube

property of coal for the gasifier operation [6]. Below T_{cv}, the solid slag layer consists of glassified solid slag and a fraction of liquid slag that shows Bingham fluid characteristics due to the phase equilibria of the slag components [7]. The slag layers prevent potential wall damage due to physical or chemical attacks by hot and corrosive gases and particles. They also facilitate the continuous removal of ash from the reactor by allowing liquid slag to be collected at the bottom of the gasifier and quenched in water. Therefore, in operating the gasifier, it is essential to ensure that the slag layer covering the entire wall while continuously discharging the liquid slag to prevent its accumulation. For example, an increase in the slag viscosity due to changes in the ash composition or low gas temperatures would increase the slag thickness. Such an increase, if not properly controlled, may lead to the blockage of the slag tap. One control measure is to inject CaO-based flux for coals with a high slag viscosity [8–10]. For low rank coals with a low T_{cv}, blending using a coal with high SiO_2 and Al_2O_3 contents or a supply of kaolinite can be considered to reduce the wear on the refractory wall [11].

Given the importance of the slag layer along the gasifier wall, many studies have been reported on the properties of the slag [5,12–18] and on the modeling of the flow and heat transfer within the slag layer [4,19–25]. For the slag flow, Seggiani [4] proposed an analytical model for integrating the momentum equation, assuming a linear temperature profile within the liquid slag layer. This model was applied to process simulations of the Prenflo gasification process. This simple model was adopted by many researchers to conduct studies on various gasifiers because it could reasonably predict the slag flow in the gasifier under typical conditions [19–22]. Li et al. [19] studied the slag flow in a coal and black liquor gasifier, and showed that the enthalpy of the slag flow considerably influenced the energy balance. Kittel et al. [20] compared the heat transfer obtained from numerical analysis using Seggiani's model and the experimental results for a Siemens coal gasifier, in which the difference in the temperature of the returned cooling water was within 10%. Ni et al. [21] compared Seggiani's model with two-phase computational fluid dynamic (CFD) simulations for the lower part of a gasifier. The velocity distributions obtained from the two models were similar, although the temperature profiles for the liquid slag in the CFD results were nonlinear. Their study illustrated the limitation of Seggiani's model for particular conditions in which the temperature within the liquid slag deviates from a linear relationship between the surface temperature and T_{cv}.

Recently, Yong et al. [22] developed a new model of slag flow to determine the boundary conditions for CFD in a pilot-scale oxycoal combustor. To overcome the limitations of Seggiani's model, this model assumed a third-order polynomial for the temperature profile within the liquid slag. However, the slag properties such as the viscosity were fixed at the average temperature within the slag layer. This model additionally considered the momentum of the particle deposition, particle capture criterion and conversion of unburned char partially submerged in the liquid slag surface [23,24]. Chen et al. applied this model as a user subroutine of a commercial CFD code and conducted simulations of a cylindrical oxy-coal combustor to investigate the ash deposition and slag flow behaviors [25].

The aforementioned models of Seggiani and Yong et al. enabled the fast calculation of slag flow and heat transfer by directly integrating the governing equations. However, this inevitably required assumptions on the temperature profile within the liquid slag and on the slag properties. In this study, a new numerical model was