Fuel 196 (2017) 532–542

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Numerical analysis on transient behaviors of slag layer in an entrained-flow coal gasifier

Mukyeong Kim, Insoo Ye, Changkook Ryu *

School of Mechanical Engineering, Sungkyunkwan University, Suwon 16419, Republic of Korea

HIGHLIGHTS

- A new dynamic model for slag layer on the wall of a coal gasifier is proposed.
- The slag layer requires 10 min or longer to adjust to new operating conditions.
- The heat absorption on the wall responds faster than the slag thickness.
- Gas temperature changes the slag layer faster than slag deposition rate.
- The temperature profile of liquid slag can be non-linear during transient states.

ARTICLE INFO

Article history:
Received 8 September 2016
Received in revised form 25 December 2016
Accepted 1 February 2017
Available online 12 February 2017

Keywords:
Ash deposition
Coal gasification
Entrained gasifier
Numerical model
Slag layer

ABSTRACT

In an entrained-flow coal gasifier with water-cooled walls, it is important to maintain an appropriate range of slag thickness on the wall for protecting the refractory and preventing blockage at the slag tap. Owing to the difficulty in measurement within the gasifier, the heat absorption on the wall and downstream syngas composition are monitored as indicators of slag thickness and gas temperature. However, there is a certain delay between these parameters that can be highlighted by the dynamic modeling of slag behaviors on the wall and reactions/flow in the gas regime. In this study, a new dynamic model for the slag layer was developed, which solves for the energy, heat transfer, and flow of the solid and liquid slag layers including the transformation between the two phases. The model was applied to a commercial gasifier varying operating parameters, and the transient behaviors of the slag layers were analyzed focusing on the thickness at the slag tap and the heat absorption on the wall. When the operating conditions changed abruptly, the slag layer required 10 min or longer to reach the new steady state. The thinning of the slag layer was faster than its thickening. In addition, the response of heat absorption was significantly faster than that for the slag thickness at the slag tap. The characteristic times of the slag layer were shorter with changes in gas temperature than with changes in the mass rate and temperature of the slag deposition. During the transient states, the temperature profile within the liquid slag became non-linear, which suggests that existing models assuming a linear temperature profile may not be appropriate for dynamic simulations.

1. Introduction

Gasification offers various routes for the use of coal in the production of various chemicals, fuels, and electricity. Most commercial coal gasification technologies adopt entrained flow reactors feeding pulverized coal in dry or slurry forms. By gasifying agents of pure or enriched oxygen, entrained flow reactors provide fast conversion into tar-free syngas at high temperatures. After coal conversion, the ash melts to form slag, which deposits onto the refractory on the walls. The slag layer plays an important role in protecting the refractory from the hot and hostile environment and in discharging the ash. In several gasifier types, such as those used by Shell, Prenflo, and Siemens, the gasifier wall is cooled using a water jacket or membrane water wall [1]. On the water-cooled wall, the slag layer facing the refractory lining solidifies, whereas the layer facing the syngas remains in the liquid phase and flows downward. The interface of the solid and liquid slag layers is determined by the temperature (T_{cv}) at which the critical viscosity of 25 Pa s is attained [2].

Maintaining an appropriate slag thickness is one of the crucial criteria for selecting suitable coal types and determining the range

---

* Corresponding author.
E-mail address: cryu@me.skku.ac.kr (C. Ryu).

http://dx.doi.org/10.1016/j.fuel.2017.02.002

Nomenclature

a	coefficient
b	coefficient
C_P	specific heat of the slag, J/kg/K
g	gravity, 9.81 m/s^2
H	enthalpy, J/s
h	convection coefficient, W/m^2/K
k	thermal conductivity, W/m/K
M	momentum, kg m/s^2
m	mass flow rate, kg/s
Q	heat transfer rate, W
r	radius perpendicular to the wall, m
T	temperature, K
V	volume, m^3
v	streamwise velocity, m/s
Δy	height of control volume parallel to the wall, m

Greek

α	angle from the horizontal plane, °
δ	thickness of slag layer, m
ε	emissivity
μ	viscosity, Pa s
ρ	density, kg/m^3
σ	Stefan-Boltzmann constant

Subscript

C	coolant (water)
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 a section of slag layer
in	inflow
j	index for a section of slag layer in the streamwise direction
L	liquid slag
M	metal tube
MC	from metal tube to coolant
out	outflow to the section below
ref	reference temperature
S	solid slag
surf	liquid slag surface facing syngas
tap	at the slag tap
wall	entire gasifier wall

of operating parameters. For example, feeding coal containing ash with an extremely high T_{cv} (or gas temperature below T_{cv}) in the lower part of a gasifier increases the slag thickness and may cause blockage at the slag tap, which is a critical operational problem [3]. However, real-time monitoring of the slag thickness is almost impossible because of the difficulty of accessing the slag tap under the hot and hostile environment of the gasifier. The gas temperature can be an indicator of the slag thickness, with which it is inversely correlated, but it is difficult to measure because of the extremely high temperatures and fly slag within the gasifier. Instead, the syngas composition and heat absorption on the wall can be monitored to indirectly obtain the information on the slag thickness. Based on the chemical equilibrium, the syngas composition downstream can be correlated with the temperature within the gasifier; however, there is a time delay due to the gas residence time within the cooling system downstream of the gasifier. The heat absorption on the water-cooled wall is used as an indicator for the gas temperature and slag thickness. However, it also involves a certain time delay because the transient behaviors of the slag layer influence the thermal resistance of heat transfer between the syngas and coolant. Therefore, the interactions between the transient behaviors of the slag thickness and heat absorption must be understood. To address this concern, this study is conducted using numerical modeling.

Numerical modeling of the slag layer is used as a boundary condition for conducting a simplified 1-dimensional process simulation or detailed computational fluid dynamic (CFD) simulation of a gasifier. The slag layer models can be categorized through analytical or numerical approaches. Analytical approaches derive algebraic functions from the conservation equations of mass, momentum, and enthalpy by assuming a specific temperature profile and slag viscosity for the liquid slag. The solid slag is treated as the boundary condition for steady-state heat transfer with a fixed interface temperature at T_{cv}. The most well-known model by Seggiani [4] assumes a linear temperature profile within the liquid slag layer. In contrast, the model by Yong et al. [5] assumes a parabolic temperature profile with a constant viscosity. These assumptions of the models facilitate the direct integration of the momentum and energy equations to acquire algebraic equations. With simple solution procedures, the models have been adopted in many process modeling and CFD studies in various gasifiers [6–12].

In our recent studies, a new numerical model based on the discretized approach was proposed and applied to detailed parametric studies for various design and operating parameters and slag properties [13–15]. Ye and Ryu's model numerically solves the governing equations in the steady state through discretization, without using assumptions on the temperature profile and slag viscosity [13]. The comparison of this model to the previous models showed that Seggiani's model is accurate for gas temperatures higher than T_{cv}, but greatly overestimates the slag thickness when the gas temperature in the lower part of the gasifier is below T_{cv}. Furthermore, the model by Yong et al. is acceptable when the gas temperature falls below T_{cv} because the temperature profile is close to parabolic. However, the constant viscosity assumption of this model may cause some discrepancies when the gas temperature is sufficiently high. Such results suggest that the existing analytical models have limitations when the assumptions on the liquid slag temperature or viscosity are not valid, although the computational costs can be minimized.

The dynamic behaviors of the slag were investigated in several studies by using a slag model coupled with a gasifier process code. Seggiani [4] showed that by changing the operating conditions in a Prenflo gasifier with water-cooled walls, the slag thickness requires as long as 2 h to reach a new steady state, whereas the gas temperature responds faster. In other studies, more simplified slag models were used. In Pednekar et al.'s study [16] on a slurry-fed gasifier, the liquid slag layer, represented by a single control volume, was coupled with detailed submodels for radiative heat transfer, char conversion, and slag deposition. The liquid slag on the refractory lining (without solid slag) responded rapidly to changes in the slurry feed rate and O_2/coal ratio. Lee et al. [17] adopted Monaghan and Ghoniem's single layer model [18] for one-dimensional modeling of a Shell gasifier. However, such