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Modeling the slag flow and heat transfer with the effect of fluid-solid slag layer interface viscosity in an entrained flow gasifier

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HIGHLIGHTS

- Modeling the slag layer characteristics with the effect of fluid-solid slag layer interface viscosity.
- The smoother the viscosity-temperature profile, the higher the effects of the fluid-solid slag interface viscosity.
- The critical viscosity can be regarded as the fluid-solid interface viscosity for the crystalline slag.

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ABSTRACT

The characteristics of slag flow and heat transfer in a gasifier are significant for controlling the operation conditions. Determination of the fluid-solid slag layer interface is a crucial procedure in the studying of slag flow and heat transfer characteristics. The varied absolute viscosities were used as the fluid-solid slag layer interface viscosity to model the slag layer properties in an entrained flow gasifier. The results showed that with the increase of fluid-solid slag layer interface viscosity, the liquid slag layer thickness increased, while the solid slag layer thickness and the liquid slag velocity decreased. Moreover, the slag layer overall thickness had a slight decrease, while the slag heat flux had a slight increase. In addition, the effects of the fluid-solid slag layer interface viscosity on slag layer characteristics with glassy slag and plastic slag were relatively higher than crystalline slag. The smoother the viscosity-temperature profile, the higher the influences of the fluid-solid slag layers interface viscosity. The critical viscosity could be approximate regarded as the fluid-solid slag layer interface viscosity when the slag type was crystalline slag during the model derivation, and the fluid-solid interface viscosity can be defined as about 100 Pa s for plastic slag and glassy slag.

1. Introduction

Coal gasification was a supporting technology for the energy and chemical industry by converting the solid fuel into hydrogen and carbon monoxide-rich syngas [1]. One of the most widespread gasification technologies was entrained flow gasification on account of its high efficient and extensive of coal species [2]. During the gasification, after the coal was gasified and fusion, most of the coal ash deposited on the wall and formed a slag layer which protected metal wall from the high temperature gas corrosion [3]. The slag layer consisted of two phases: the liquid layer heated by the high temperature syngas and the solid layer cooled by the refractory wall [4]. Determination of the interface of solid phase and fluid phase was a crucial factor in the studying of slag layer characteristics. Therefore, the interface criterion of solid and liquid slag phase was a significant research in gasifier.

Experiment study for slag flow and heat transfer in an industrial gasifier is limited and difficult due to the high temperature and pressure environment [5–8]. Several models have been proposed to describe the slag flow and heat transfer behavior in entrained flow gasifier. Seggiani [9] had built a simplified model to simulate the time varying slag flow characteristic in a Prenflo entrained flow gasifier, which was widely used in many studies [10–16]. This model was based on the conservation equation and some assumptions. One of most crucial assumption was that the

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Nomenclature

c_s	slag specific heat (J/kg K)
D	gasifier diameter (m)
g	gravitational constant (m/s^2)
h	convective heat transfer coefficient (W/m^2 K)
m_{ex}	vertical outlet slag mass flow rate per unit (kg/s)
m_{in}	mass flow of particle deposition per unit (kg/s)
q_{flux}	heat flux through the slag (W/m^2)
q_{in}	heat flux to the slag surface (W/m^2)
q_{out}	heat flux from the slag to the refractory layer (W/m^2)
T_o	slag temperature at slag-gas interface (K)
T_{cv}	temperature of critical viscosity (K)
T_f	slag flow temperature (K)
T_g	gas temperature (K)
T_{mr}	metal-refractory wall interface temperature (K)
T_{mw}	water-metal wall interface temperature (K)
T_w	refractory-slag interface temperature (K)
u	slag velocity at distance x from slag-gas interface (m/s)
x	the distance from the slag-gas interface (m)

Greek letters

δ_l	thickness of liquid slag layer (m)
δ_m	thickness of metal wall (m)
δ_r	thickness of refractory wall (m)
δ_s	thickness of solid slag layer (m)
ε	emissivity
θ	slope of the wall (°)
λ_l	thermal conductivity of liquid slag (W/m K)
λ_m	thermal conductivity of metal wall (W/m K)
λ_r	thermal conductivity of refractory wall (W/m K)
λ_s	thermal conductivity of solid slag (W/m K)
μ_l	liquid slag viscosity (Pa s)
μ_{sl}	solid–liquid slag layer interface viscosity (Pa s)
ρ	slag density (kg/m^3)
σ	blackbody radiation coefficient (W/m^2 K^4)

Subscripts

0	slag surface or $x = 0$
cv	critical viscosity
f	slag flow
g	gas
i	slag unit
in	inflow to the slag
l	liquid slag
m	matel wall
mr	matel-refractory wall interface
mw	metal wall-water interface
out	outflow from the slag
r	refractory wall
s	solid slag
sl	solid-liquid slag layer interface
w	refractory wall surface

transition temperature of liquid and solid slag layers was the temperature of critical viscosity (T_{cv}), which would greatly simplify the derivation process during the simulation. Yong et al. [17–19] proposed a modified model to simulate the slag layer in solid fuel gasification and combustion, in which the temperature profile was assumed as a cubic polynomial and the considered the shear stress by depositing particles. The slag flow under the temperature between the T_{cv} and the flow temperature (T_f) was considered for the throat part of gasifier [20]. Li et al. [21] calculated the heat transfer of slag layer by the discretization of the velocity in a black liquor recovery boiler. The heat transfer from numerical analysis and the experimental results was compared in Ref. [22]. Ye et al. [23,24] built the slag flow model with the control volume method, the unique feature was that the deposition from the gasifier was regarded as a new control volume which attached to the original slag. In general, the slag model for a gasifier included slag flow and heat transfer model, particle model and 3-D model [25]. The particle model was mainly to describe the particle deposition or particle capture process [26–29]. The 3-D model was determined by the slag properties and operation conditions of gasifier, which can obtain through the simulation software and formula [30–37]. The slag flow and heat transfer model were based on the conservation equations and some simplified assumptions [38–40], and different assumptions or derivation process led to the various modeling results.

In most of the literatures, the temperature of critical viscosity (T_{cv}) was used as the transition temperature between the liquid and solid slag layers [9,17–19,23,24]. Generally, T_{cv} referred to the temperature at which the viscosity rapid changes, which could be calculated by the composition of slag [41]. The T_{cv} is a fixed characteristic parameter for a slag which can be calculated from the formula or obtained from the viscosity-temperature profile. While most of the literature uses the T_{cv} as the liquid-solid slag interface temperature, without considering how much the impact of this assumption on the calculation results. In this study, we model the slag layer properties with different interface viscosity, thus attempting to redefine the liquid-solid slag interface according to the model results. The theoretical knowledge of determination of liquid-solid slag interface is not enough and the purpose of this work is to improve the theoretical knowledge construction.

This paper uses the absolute viscosity as interface criterion of solid and liquid slag layers. The objective is to study the effects of the fluid-solid interface viscosity on slag layer properties in entrained flow gasifier. The modified model is based on Seggiani's [9] work and analyzed using numerical method. Several typical slags (crystalline slag, plastic slag, and glassy slag) have been used to investigate the effects of the fluid-solid interface viscosity with different viscosity-temperature characteristics.

2. Numerical models

2.1. Slag flow and heat transfer model

Fig. 1 shows a typical slag layer unit along the wall in an entrained flow gasifier. The slag flow and heat transfer model is established in accordance with Seggiani's [9] method which based on a series of assumptions. One of the most important assumptions

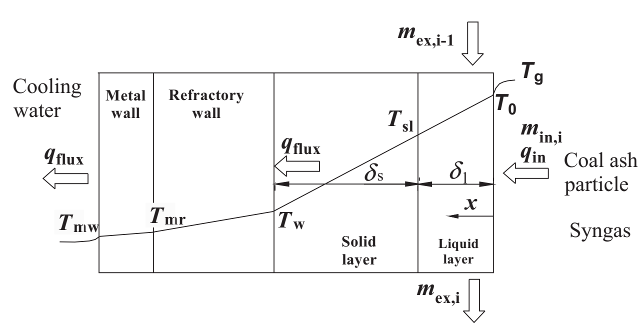

Fig. 1. Schematic diagram of slag layer for unit *i* along the wall.