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Combined slag flow model for entrained flow gasification

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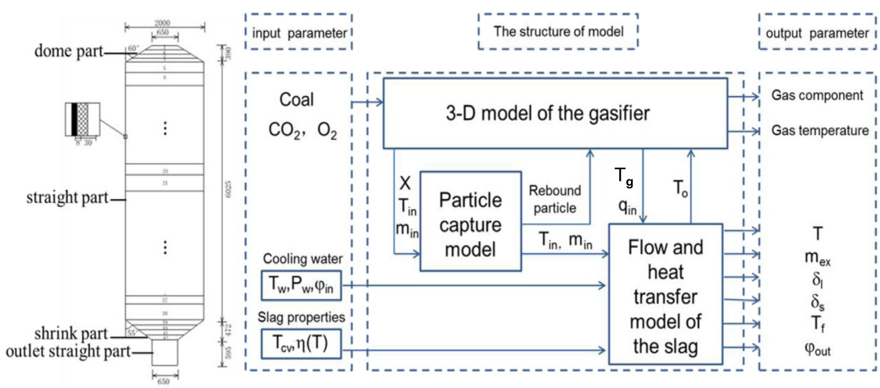
HIGHLIGHTS

- A combined slag model was developed to describe the slag characteristics and gasification process in entrained flow gasifier.
- The influence of particle behavior on slagging is demonstrated.
- A comparison was made between the membrane wall gasifier and the refractory wall gasifier based on thermal resistance.

GRAPHICAL ABSTRACT

Objective of the simulation and structure of the slag model.



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ABSTRACT

A slag flow and heat transfer model coupled with a particle capture sub-model and 3-D gasifier model was developed to describe the slag characteristics and gasification process in entrained flow gasifier. A criterion for particle capture was used to evaluate the interaction of particles colliding with the wall. Two kinds of gasifiers were simulated using the developed model: the membrane wall gasifier and the refractory wall gasifier. The model was proved reliable by comparing the simulation with industrial results. Sensitivity of the model was analyzed. The model predicted the local thickness of the solid and liquid slag layers as well as the temperature distribution across the slag layer. Further study investigated the influence of particle behavior on slagging in the gasifier. In addition, a comparison was made between the membrane wall gasifier and the refractory wall gasifier. The results indicated that temperature of critical viscosity and the thermal conductivity of the slag were crucial factors in determining the accuracy of the combined model. The slag of the membrane wall consisted of both a solid and liquid slag layer. The internal surface temperature of the steel was lower than 540 K, which decreases the occurrence of thermal corrosion. The larger particle was beneficial to the capture efficiency and formation of slag layer, while the smaller one favors high carbon conversion. For the membrane wall gasifier, the thermal resistance of the solid slag layer contributed to the protection of the silicon carbide layer and membrane wall. For the refractory gasifier, thermal resistance of the refractory lining and environment convection were the major parts.

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Nomenclature

Symbols

A_i	area (m^2)
C_p	specific heat ($kJ\ kg^{-1}\ K^{-1}$)
FT	flowing temperature (K)
G	capture probability (%)
m_{in}	particle feeding rate ($kg\ m^{-2}\ s^{-1}$)
P_w	pressure of cooling water (K)
q_{in}	heat flux into the slag (w)
q_{out}	heat flux out the slag (w)
q_m	heat flux out the SiC (w)
q_{mo}	heat flux out the membrane wall (w)
T_{cv}	temperature of critical viscosity (K)
T_f	outlet temperature of cooling water (K)
T_g	temperature of gas (K)
T_{in}	particle temperature (K)
$\overline{T}_l$	mean temperature of the liquid slag (K)
T_o	surface temperature of the slag (K)
T_m	temperature of the membrane wall (K)
T_s	temperature of the slag (K)
T_w	inlet temperature of cooling water (K)
u	velocity of the gas ($m\ s^{-1}$)
v	velocity of the slag ($m\ s^{-1}$)
X	carbon conversion (%)
z	distance from the slag surface (m)

Greek letters

β	angle of the slag (°)
δ_l	thickness of the liquid slag (m)
δ_m	thickness of the membrane wall (m)
δ_r	thickness of SiC (m)
δ_s	thickness of the solid slag (m)
φ_{in}	gas fraction in the inlet (%)
φ_{out}	gas fraction in the outlet (%)
η	viscosity of the slag (Pa s)
η_{cv}	slag viscosity at T_{cv} (Pa s)
λ	conductivity of the slag ($W\ m^{-1}\ k^{-1}$)
λ_m	conductivity of the membrane wall ($W\ m^{-1}\ k^{-1}$)
λ_r	conductivity of the SiC ($W\ m^{-1}\ k^{-1}$)
ρ_m	density of the membrane wall ($kg\ m^{-3}$)
ρ_r	density of the SiC ($kg\ m^{-3}$)
ρ_s	density of the slag ($kg\ m^{-3}$)

1. Introduction

Gasification is a technological process that is conventionally employed to convert the solid feedstock, such as coal, petcoke and biomass, into clean syngas consisting primarily of hydrogen and carbon monoxide [1]. Among the various gasification technologies, entrained flow coal gasification is mostly widely used in the production of numerous chemicals and shows favorable prospects on the Integrated Gasification Combined Cycle (IGCC). Generally, entrained flow gasification is classified by the lining type of the gasifier chamber. Two types of lining (refractory brick wall or water-cooling membrane wall) are used in the gasifier chamber to protect the steel walls. During the operation of the gasifier, the inorganic compounds in the coal form an incombustible ash residue. In an entrained coal gasifier, most of the ash is deposited on the inner wall of the chamber and then flows down as molten slag. The remaining ash is entrained as fly-ash by the syngas and enters the scrubbing system. In order to avoid any obstruction, the fusibility and flow properties of the ash and the temperature inside the gasifier must enable the unobstructed removal of the slag through the tap hole. Therefore, understanding the behavior of the slag is necessary and critical for further improvements to the reliability and availability of entrained flow gasifier. Due to the difficulties associated with real-time observations, constructing a comprehensive slag model is an effective way to investigate the slag behavior in the gasifier.

Several models have been proposed to predict slag formation and its flow characteristics in an entrained flow gasifier. Chen et al. [2] studied the slag behavior in an oxy-coal combustor by introducing the effect of wall burning and the Weber number. Bockelie et al. [3] investigated the slag thickness of the GE and MHI gasifier with a new numerical scheme. Yang et al. [4] discussed an oxygen-staged slagging gasifier with a reactor network model. The slag model used in Otaka et al. [5] provided an evaluation method for the molten-slag from coal gasifier without taking the particle effects into account. Essentially, modeling the slag behavior of the entrained gasifier primarily involves three aspects: 3-dimensional CFD simulation of the gasifier, the slag flow and heat transfer model, and the particle capture model. A lot of researchers have developed 3-D gasifier models and showed their reliability [6–9]. Seggiani [10] proposed a one-dimensional time-varying slag flow and transfer model that has been widely accepted in previous studies [11,12]. However, for the particle capture model, various opinions exist as to the most viable model. For example, Ni et al. [13] simplified the collision of particles with the wall as liquid–solid wall interactions and introduced the maximal rebounded energy, Ee^*, to classify the particles. But the collision of particles to the wall is more like solid–solid interaction. Tominaga et al. [14] and Lee et al. [15] used critical viscosity to distinguish the particle behavior, so the selection of the critical viscosity is crucial for the accuracy of the model.

This paper presents a combination of the Wu et al. [6] and Seggiani [10] models. Moreover, a capture criterion is introduced in accordance with the experiment conducted by Li et al. [16]. The combined model provided detailed information about slag accumulation and flow on the wall. The sensitivity of the model was analyzed based on slag thickness. Particle behavior was investigated according to particle size. Thermal resistance information was used to conduct a comparison between the refractory wall gasifier and the water-cooling membrane wall gasifier.

2. Slag model

The slag model was developed to better predict the wall boundary conditions for a CFD framework. Fig. 1 shows the mass and heat transfer near the wall of the water membrane gasifier. There is a SiC layer inside the membrane to protect the steel material. Most of the unburned ash is deposited on the surface of the SiC before forming a solid or liquid slag layer (based on slag temperature). The liquid slag flows along the internal wall of the reactor chamber, with some re-solidifying during its movement. The heat flux passes through the slag layer, SiC layer and membrane wall, successively. Based on mass, energy and momentum conservation, this paper adopts the following assumptions: (1) Slag flows downwards (i.e. no reverse flow); (2) The temperature of critical viscosity is the transition temperature between the solid and liquid slag; (3) Liquid slag is considered as Newtonian fluid and solid slag is assumed unmovable; (4) Slag thickness is much smaller than the diameter of the chamber.